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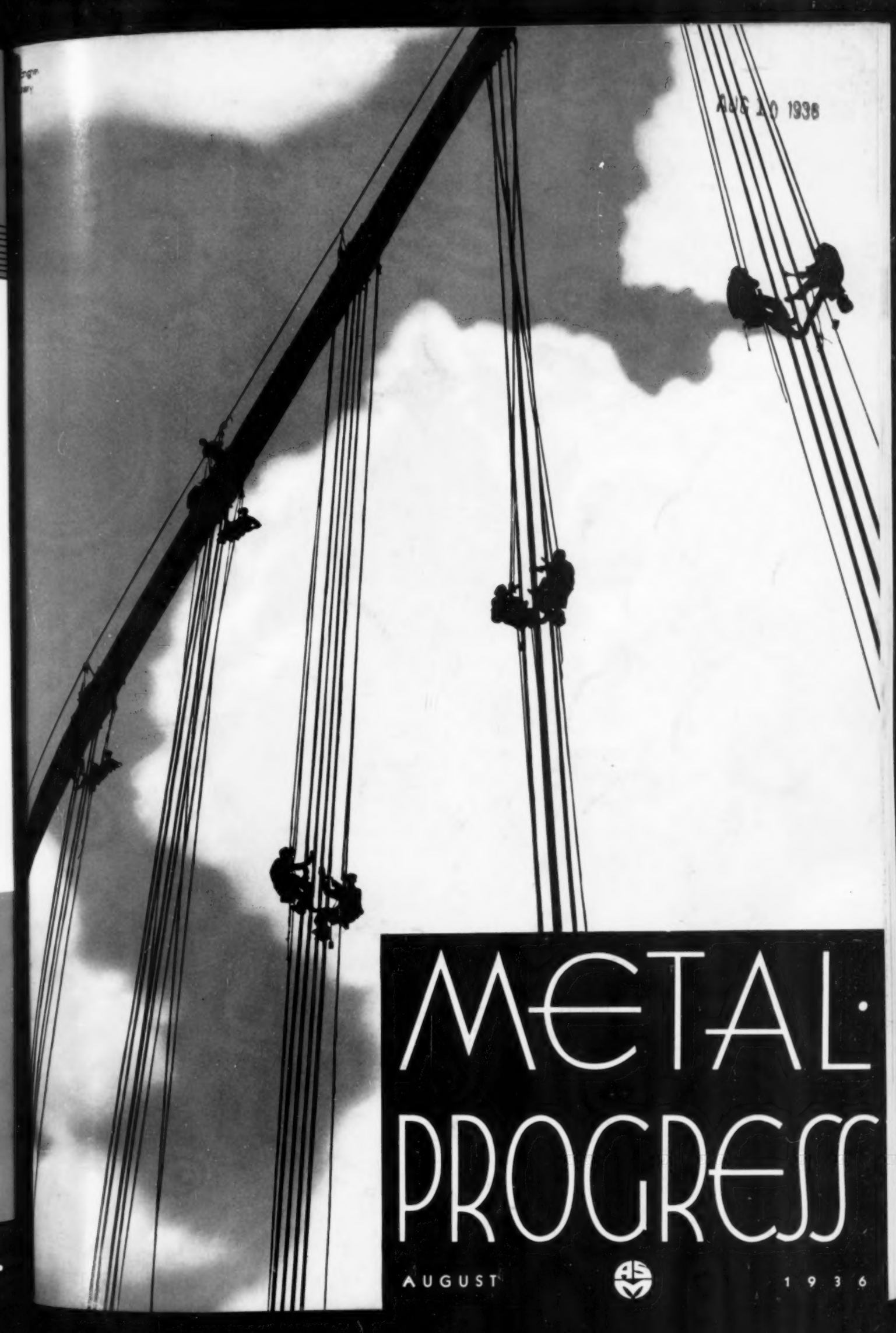
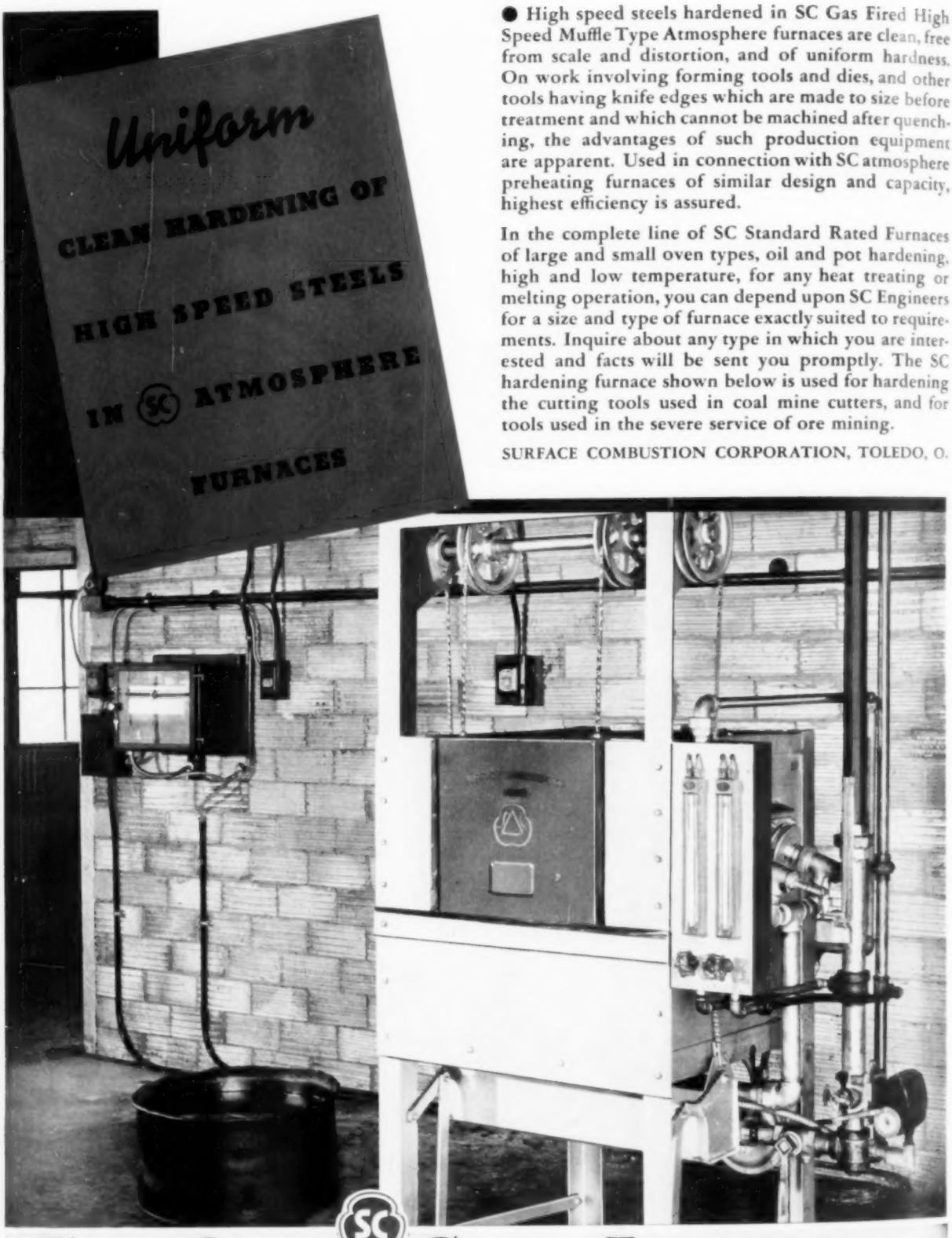


METAL PROGRESS

AUGUST 1936



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METAL PROGRESS

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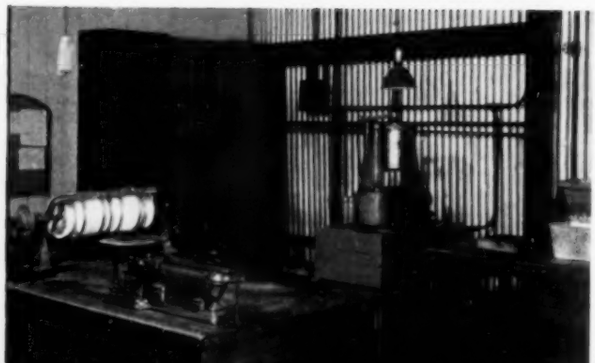

No. 2

Ceramics

Ceramics—in the form of refractory materials—play an important part in modern alloy steel manufacture. The nature and quality of the materials used for lining furnaces, ladles and metal hot tops have definite influence on both the quality of the steel and the cost of production.

Recognition of the importance of refractories is seen in the Timken Ceramic Research and Testing Laboratory, two views of which are shown.

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METAL PROGRESS

Vol. 30 August, 1936 No. 2

Ford Alloy Castings

copper used extensively

By R. H. McCarroll
and J. L. McCloud
Ford Motor Co.
Dearborn, Mich.

INTEREST in the new cast alloy steels and irons, utilized in Ford cars in place of forged parts, is evidenced by several articles in American publications since they entered production. The U. S. patent office has allowed us a number of patents on compositions and products, which shows that the examiners consider them new and useful.

The natural primary questions to be answered are, "What, why and how are these alloy ferrous castings made?" Let us then consider, first, "What?"

In the alloy cast irons, so-called, we have three types, *(a)* nickel-chromium, *(b)* copper, and *(c)* a copper-chromium iron. They contain approximately 3.25% carbon and may therefore be reasonably classed as cast irons.

In the alloy cast steels, so-called, we also have four types, *(a)* copper, *(b)* copper-molybdenum, *(c)* copper-chromium, and *(d)* tungsten-chromium-copper. These have substantially lower carbon contents than the cast irons, as will be shown below.

The answer to the next question "*Why* are alloyed ferrous castings made?" is that they improve quality and secondarily lower cost. The quality improvements are to increase strength for the same weight of metal, achieved by better distribution, and this in turn makes it easier to balance such parts with consequent lowered vibration. Then, too, improved wear resistance is obtained. Lowered weight is particularly important in reciprocating parts and in parts that are components of the unsprung weight. Decreased cost may come from lowering the cost of production of the rough part, by having less metal to remove in machining and by allowing less expensive machining methods.

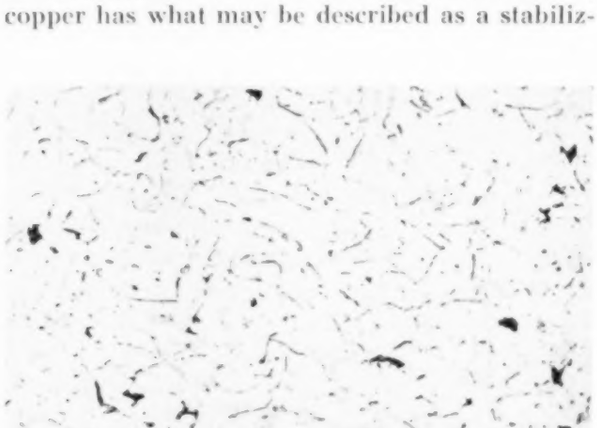
As to the "How?" the answer is difficult to give in a few words, and is best left for the detailed notes now to be given.

First in order of these cast irons is the nickel-chromium type. This is made by adding alloy to what we term "D" iron, a medium carbon iron of 3.15 to 3.40% carbon. This alloy is used for brake drums whose principal requirement is hardness (as measured by the Brinell test) associated with definite microstructure, and whose secondary requirement is machinability. The melt used contains 15% steel scrap; the addition is 0.15 to 0.35% chromium, which is the hardener, and 0.15 to 0.35% nickel, which makes these iron castings machinable.

(We might note here that "machinability" is such a relative term that it is often misunderstood. Probably each machine shop has a different definition of the term, and each in turn is influenced by the demands of the engineering department, the metallurgical department, and the management for quality of performance of the part machined. In general, the Ford Motor Co. policy is to demand a high level of hardness, even at the expense of higher machining costs.)

These brake drums of nickel-chromium cast iron perform well and are used, bolted to cast hubs, in passenger cars. Life of brake band linings is satisfactory; ample experience shows that the drums resist scoring, and most important, when properly designed they do not require a high pedal pressure nor do they "fade out." These are the major factors to consider in a brake design, at least from the material viewpoint, but since brakes are such a big subject, they will not be further discussed in this article.

The second class of alloy cast irons contains copper. In this class we have three distinct varieties, two with the same copper content of 0.50 to 0.75%. The first is for cylinder blocks, called by us "A" iron. For this we have 15 to 20% steel scrap in the melt, carbon is from 3.15 to 3.40%, and the silicon is 1.80 to 2.10%. For cylinder blocks it is generally recognized that the hardness in the bore must be maintained high enough to resist wear of piston rings, and we find that copper additions make such iron more machinable. The graphite also has a more finely divided character, as shown in the micro below; copper has what may be described as a stabilizing effect on the graphitization of carbon. This is evident in a diminished chilling effect on thinner sections adjacent to more massive ones, and a general tightening of the structure in these heavier sections.



Finely Divided Graphite in V-8 Cylinder Block Iron. Unetched; 100 X. Analysis 3.15 to 3.40% carbon, 1.80 to 2.10% silicon, 0.50 to 0.75% copper

As a definite example, copper aids in making sounder castings around valve ports without too great hardness in the bore sections. If we achieved this by lowering the carbon we would approach a tendency to cracks; to achieve this, on the other hand, by increased silicon is to induce too much "openness" or porosity. We find copper even more satisfactory than nickel for these effects, and at less cost.

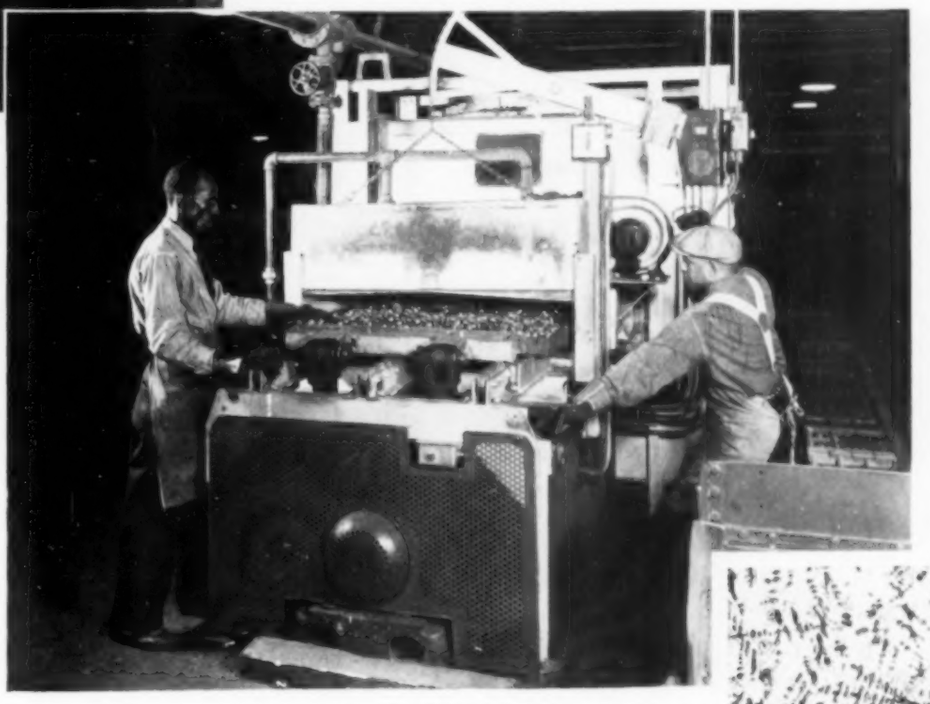
In iron for flywheels the copper addition is as above (0.50 to 0.75%) and is essentially for the purpose of improving machinability with, incidentally, increased strength. A lower amount of steel scrap is charged (5 to 10%) and higher carbon is obtained, 3.30 to 3.60%, manganese is 1.00 to 1.25%, but a lower silicon of 1.40 to 1.80% is used. In a flywheel the sections are so great that some element must be introduced to "close the grain." As already pointed out, copper accomplishes this better than a low silicon content, since the copper does it without sacrificing any machinability.

For push rods we have quite another variety of the copper alloy iron. This is a chill casting made in permanent molds with sand cores, and has only 0.30 to 0.65% silicon with 0.15 to 0.50% manganese and 3.60 to 3.90% carbon. The copper addition is 0.75 to 1.00%. The action of the copper in such a composition is interesting, since it adds strength to the castings even in the hard condition. From the photograph alongside it can be readily appreciated that this push rod has quite changed in its outward appearance from the one in other designs of gas engines.

These are heat treated to remove casting strains, but not heated hot enough or long enough to make the iron gray. In other words, the carbon content is retained in the combined state, and this white iron is what gives the wear resistance. The copper functions by giving the matrix the necessary toughness to counteract the inherent brittleness of the high content of undecomposed iron carbide or cementite.

The push rod produced in this way definitely lowers the reciprocating weight, since it is not only hollow but also has cast-in windows. The windows are produced in an interesting manner since they are formed by projections on the iron molds "kissing" against the cylindrical core.

mean that while the casting is largely gray the cam tips are white for a specified distance. This control is exercised first at the cupola by examining test bars cast in dry sand, 1¼ in. round by 6 in. long. Every ladle of iron is sampled in this way and grain of the test-bar fracture noted. Periodically cam castings are broken to determine the chill depth; this must be held within ⅛ in. The chromium addition is dictated by the fracture tests, and may be up to the 0.25% noted above, chromium tending to make the iron whiter. A swing in the opposite direction may likewise be controlled by additions of powdered ferrosilicon, also in the ladle.



This also eliminates any roughness on the outside of the rod which would have to be removed. A noteworthy point in the design of these windows is their angularity to the axis of the rod which makes centerless grinding a smooth, accurate operation. In fact, the only finish is grinding the outside in a centerless machine and grinding the "rod" to length.

Ford Engine Push Rod, Its Structure and Method of Manufacture. Analysis 3.60 to 3.90% carbon, 0.30 to 0.65% silicon, 0.15 to 0.50% manganese, 0.75 to 1.00% copper. Micro etched with 5% nital; 100 X. Castings are made in permanent molds and sand cores, and then annealed in controlled atmosphere

The camshaft is also essentially a copper-chromium alloyed iron of the third type mentioned at the outset. This has a carbon content of 3.30 to 3.65%, manganese 0.15 to 0.35%, silicon 0.45 to 0.55%, high copper (2.50 to 3.00%) and may have up to 0.25% chromium. Here we have a controlled chill casting, produced without external chills or mold chills, and the desired condition is obtained without any heat treatment whatsoever. Photographs on page 36 show the fracture of a cam section and its microstructure.

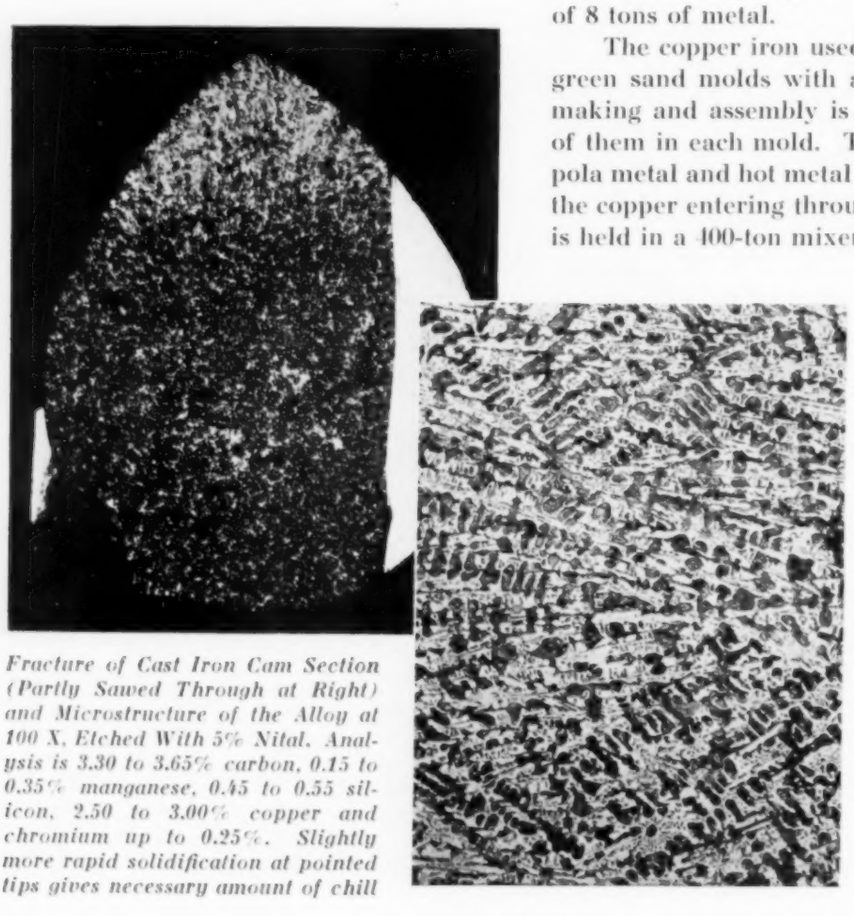
By the words "controlled chill" just used we mean that while the casting is largely gray the cam tips are white for a specified distance. This control is exercised first at the cupola by examining test bars cast in dry sand, 1¼ in. round by 6 in. long. Every ladle of iron is sampled in this way and grain of the test-bar fracture noted. Periodically cam castings are broken to determine the chill depth; this must be held within ⅛ in. The chromium addition is dictated by the fracture tests, and may be up to the 0.25% noted above, chromium tending to make the iron whiter. A swing in the opposite direction may likewise be controlled by additions of powdered ferrosilicon, also in the ladle.

The use of copper lessens any innate tendency for the swing in either direction; in fact it is quite common for the foundry to operate day after day without additions of either of the alloys ferro-chromium or ferro-silicon in the ladle. This we believe is due to this stabilizing action of high copper. It should be recognized that camshafts must be very stiff or

rigid so as not to bend a measurable amount in service. That being the principal requirement, these camshafts of alloyed cast iron are giving excellent service; there is no measurable wear on either the shaft or push rod. (Incidentally, we have white iron running or rubbing on white iron in the assembly of camshaft and push rod, the difference in structure being principally in the size of the dendrite pattern.) Here too we have eliminated all rough machining, as the cams are cast to width; in effect the ordinary rough machining operations are "cast in." Nearly all the necessary machining is confined to rough grinding and finish grinding of the cams and bearings.

Iron for Cylinder Blocks Is a Mixture of Blast Furnace Pig and Cupola Iron Containing Copper. This is stored in a 400-ton mixer, reheated as desired in a 15-ton electric furnace (left), transferred to an air furnace (right) acting as a reservoir for the automatic pouring machine shown on page 38 serving an adjacent conveyor line of molds

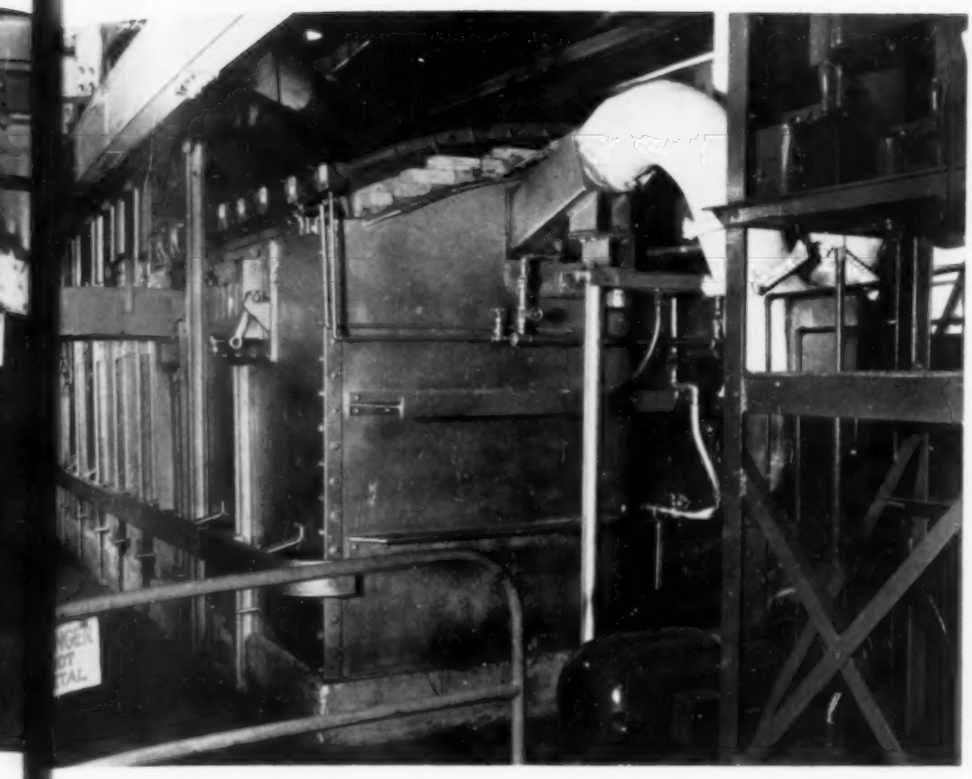
Answering the question "How are these alloy cast irons made?" let us consider first the nickel-chromium type for brake drums. These are made in a green sand mold and the melt is in a cupola. The alloy additions are all made in the cupola in the form of rustless steel scrap. However, one supplier is making this type of iron in a Brackelsburg furnace. This is a barrel or kiln-shaped furnace fired with pulverized coal. The furnace rotates continuously; it is end fired and has a capacity of 8 tons of metal.



Fracture of Cast Iron Cam Section (Partly Sawed Through at Right) and Microstructure of the Alloy at 100 X, Etched With 5% Nital. Analysis is 3.30 to 3.65% carbon, 0.15 to 0.35% manganese, 0.45 to 0.55 silicon, 2.50 to 3.00% copper and chromium up to 0.25%. Slightly more rapid solidification at pointed tips gives necessary amount of chill

The copper iron used in the cylinder block is cast in green sand molds with a multitude of cores. The core making and assembly is a story in itself, there being 46 of them in each mold. The melt is a combination of cupola metal and hot metal from the adjacent blast furnace, the copper entering through the cupola charge. This mix is held in a 400-ton mixer at comparatively low temperature (about 2500° F.) and the analysis is adjusted here if necessary. The metal is drawn off as required, 15 tons at a time, and transferred to an electric furnace for reheating to a proper pouring temperature. As shown in the views above it is then transferred to an air furnace which really acts as a reservoir for the automatic pouring car shown on page 38. Temperatures are regularly measured with optical pyrometers for careful control.

The flywheel is a green sand casting of straight cupola metal, all analysis con-



trol being in the original charge for the cupola.

The push rod is a permanent mold casting (see the group of photos on page 35). Molds are made of gray iron; the center is cored with dry sand. The rods are annealed at 1650° F., cooled in the furnace extension at a definite rate. The furnace itself has a controlled atmosphere for so-called bright annealing. The melting is done in a small cupola, the copper being part of the charge. The cupola is tapped into a holding ladle which is actually a small oil fired furnace from which the metal is drawn off into 50-lb. hand ladles for pouring into the molds.

Camshafts are made in green sand molds. The melt is in a cupola, the copper again entering at that point; other possible chemical adjustments are made in the ladle as described above. Optical pyrometric measurement controls the temperatures.

Alloy Steel Castings

Of the four types of alloy steel castings, first in order is the low carbon, copper alloy (carbon 0.15 to 0.35%, manganese 0.40 to 0.60%, silicon 0.60 to 0.80%, and copper 1.50 to 2.00%). Clutch pedals are typical parts made of this analysis, the general requirements being satisfactory strength, ductility, and machinability. Here we have a metal with satisfactory strength combined with higher ductility than that found in ordinary malleableized iron castings (although the Ford malleable iron analysis with special heat treatments is an exception to this rule). The silicon contributes in part to the necessary fluidity and freedom from casting shrinks. It also helps to hold the copper in solution and copper furnishes the balance of the required fluidity and soundness.

Subsequent heat treatment of these low carbon copper steels consists of the ordinary straight anneals. Parts are also made that require carburizing, hardening in an oil quench and drawing to relieve strain. The hardness of these carburized parts meets our regular practice, Rockwell C-58 to 60.

The rear axle housing for the Ford truck may be cited as a typical example of a second variety of cast copper steel. This is a medium carbon type, having a carbon of 0.50 to 0.60%, manganese 0.40 to 0.60%, silicon 0.60 to 0.80%, and with copper of 1.50 to 2.00%. The general requirements that may be cited are not particularly different from those mentioned immediately above, but in these housings we have much greater sections and weights, in which we wish to have as high elasticity as possible without sacrifice of the resistance to shock (ductility). These housings are annealed with a controlled rate of cooling, first in the furnace and afterwards in air. The hardness obtained is 170 to 180 Brinell.

This housing is an example of the economical advantage of a steel casting, since the metal may be properly distributed in it to meet the design requirements. Each half was formerly a welded assembly of a steel tube with malleableized iron bell and steel forgings. Actually the casting weighs less than the former assembly and is equal in rigidity or stiffness. The savings achieved are due to reduced machining costs with less metal to remove and the elimination of the welding formerly required.

The second type of alloy steel goes into the higher carbon range (carbon 1.40 to 1.60%, manganese 0.70 to 0.90%, silicon 0.90 to 1.10%, copper 1.50 to 2.00%, and molybdenum 0.10 to 0.20%). A typical part is the brake drum, of unusual design, shown on the opposite page. The wheel hub is cast integrally with the drum surface and the rest of the wheel is bolted to the hub at the drum circle. For this reason it is necessary to have a high strength casting, especially in the rear hubs where the drive is through a key, cut in a tapered hole.

In order to get a mental picture of this new type of wheel assembly, consider that the former practice was to use a steel forging for the hub with a gray iron ring for the braking surface. The loads that this new alloy steel casting has to withstand, acting as combination hub, wheel center and brake drum, come from all directions and are not only static but dynamic as well.

The problem of strength is further complicated by the requirements of a good braking surface. Requirements for brake surfaces have been referred to above in the discussion of alloy cast irons, and to these are now added those for a hub and wheel. We say "wheel," since in service these steel castings virtually back up and become part of the wheel.

The heat treatment consists of a carefully controlled and prescribed furnace cooling in order that the structure is not completely broken up to the iron and graphite stage. It should be lamellar pearlite with only small nodules of graphite, a combination giving an excellent braking surface. It might be thought that either the alloy iron described at the outset of this article or the copper-molybdenum alloy steel would become the single standard; as a matter of fact, the use of both designs has been due to the necessity of distributing the production to the capacity of available foundries.

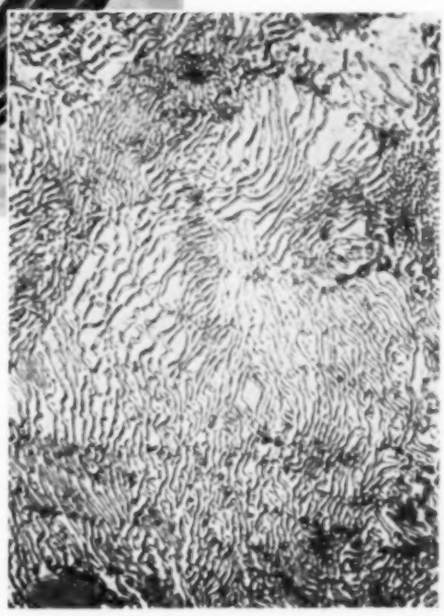
Available foundry capacity also affects the type of furnace used for melting these steel castings. Either the acid electric furnace or Brackelsburg is satisfactory. The alloy is added with the cold scrap charge, unless otherwise noted. Pouring temperatures are accurately and continuously controlled with optical pyrometers.

In the steel hub castings made to be used with the alloy iron drums, the composition is modified from that given immediately above by eliminating the molybdenum and reducing the manganese to the range 0.40 to 0.60%. This is due to the fact that we can allow the formation of free ferrite in such castings, no part of which acts as a brake drum.

Iron From an Air Furnace at Left Runs Continuously Into Trough of Casting Car; This Has an Overflow Lip at Rear Which Is Spotted Over Pouring Basin on a Passing Mold (On Conveyor Line Hidden Behind Casting Car)

assemblies and such routine tests are made. Cast alloy steel hubs are equally as good as forged ones; tests below zero as well as at room temperature prove this.

The next alloy steel casting to be considered is, in chronological sequence, the first alloy type we developed — specifically the crankshaft steel. The analysis is carbon 1.35 to 1.60%, manganese 0.60 to 0.80%, silicon 0.85 to 1.10%, chromium 0.40 to 0.50%, and copper 1.50 to 2.00%. This has been well described in an article by E. F. Cone in *Metals and Alloys* last October.



Saving in Unsprung Weight With No Loss in Endurance and Toughness Is Achieved by Making Wheel Hub, Center and Brake Drum in One Alloy Steel Casting. Heat Treated to Full Pearlitic Microstructure. Analysis: 1.40 to 1.60% carbon, 0.70 to 0.90% manganese, 0.90 to 1.10% silicon, 1.50 to 2.00% copper, 0.10 to 0.20% molybdenum. Photomicrograph is at 1000 diameters, etched with 5% nital

The reasons for the copper addition are manifold. First, it increases the fluidity of the metal and decreases shrinkage; in addition it plays an important role in reducing the time of annealing. The crankshaft is, of course, a complicated piece; warpage was the main difficulty to overcome at the start, and even now must be carefully watched and guarded against. This warpage problem is encountered in both foundry and heat treatment departments. Copper does affect foundry warpage but is of utmost assistance in reducing the annealing cycle and hence warpage during heat treatment. The maximum amount of copper useful for this purpose is about 3%, but above 2% the physical properties of the shaft would fall off, probably due to the presence of free copper.

Silicon, on the other hand, controls the copper solubility and (along with the copper and carbon) the fluidity and casting properties. About half as much silicon as copper is required in order to cast shafts satisfactorily of the carbon range given above. Copper may also affect the formation of primary graphite and by this action indirectly reduce foundry warpage. The chromium addition is for improving the wearing properties, and is limited by machinability considerations;

Just as indicated before, the combined hub, drum and wheel center is a case where increased strength is secured together with a lower weight, unsprung weight. Too much emphasis cannot be given to this. The reason is that in castings metal can be placed where it is wanted; we are not limited by requirements of draft in the forging dies, and may have ribs where we want them. With intricate dies this might also be true for some forgings, but the casting in general does not present so many manufacturing difficulties. When metallurgists found alloys that could be successfully cast and later machined, and would have the required strength, they were used. In these alloys being described we find that we have succeeded.

As proof of this success in meeting the strength requirements, the brake drum hub casting with a wheel mounted on it is being regularly run in a rotating fatigue test. The set-up is in a heavy boring machine which allows the assembly to be radially loaded while the wheel is rotating on the table. A life of 100,000 revolutions was the usual run at test conditions with forged steel hubs and cast iron drums. The new and lighter cast alloy steel hub and drum give equally good life. Years of practical service have confirmed this. We have also always considered impact strength of utmost importance in wheel and hub

furthermore high chromium steel castings of this carbon range are very difficult to anneal. The chromium content chosen gives, after the heat treatment applied, thin lines of cementite forming a network around a spheroidized pearlite matrix. The chromium carbides uniformly distributed throughout the matrix offer hard particles that resist wear.

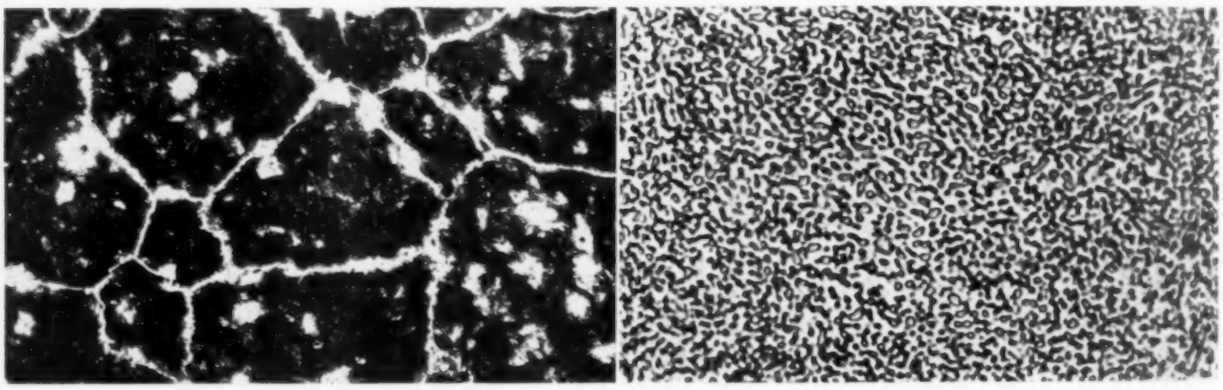
Crankshafts of this composition are heat treated in gas fired furnaces as follows: Heat to 1650° F., hold for 20 min., air quench to a minimum of 1200° F., reheat to 1400° F. and hold 1 hr., cool in furnace to 1000° F. in another hour.

The alloy for casting is melted in four 15-ton electric furnaces according to the latest approved practice. The charge is made of approximately 50% return shop scrap (gates and risers) and 50% steel scrap. Molding practice is unique, in that four shafts are cast simultaneously in a multiple mold made of a stack of slab-like cores.

An impact test has been devised where shafts must withstand a 50-lb. weight falling 40 in. on the flange at the center bearing while supported on the two end bearings.

Considerable savings in cost of production resulted from the adoption of the new alloy for crankshafts, and their actual use has been very successful. The new cast shaft when finished weighs about 10% less than the forged shaft. The forged shaft weighed approximately 83 lb. in the rough and 66 lb. after machining; the cast shaft weighs 69 lb. before machining and 60 lb. finished. Thus the amount of metal removed from the forging was 17 lb. as against only 9 lb. for the casting — a decided saving in itself. Since September 1933 over 2,000,000 cast shafts have been produced and assembled.

This is again an example of economy in design in the use of cast metal instead of forgings. In either case it is a single piece, but the ability



Structure of Crankshaft as Cast (100 X) and After Heat Treatment (1000 X). Etched with 5% nital. Composition: 1.35 to 1.60% carbon, 0.60 to 0.80% manganese, 0.85 to 1.10% silicon, 0.40 to 0.50% chromium, 1.50 to 2.00% copper

Representative physical properties of the alloy in the cast crankshaft are as follows:

In transverse test bars, 1 in. square on 12-in. centers, the breaking load is 9450 lb. and the deflection 0.425 in.

Tension tests on 0.505 round bars yield:

Ultimate strength	107,500	psi.
Elastic limit	92,000	psi.
Elongation in 2 in.	2.75%	
Reduction of area	2.25%	
Modulus	29,000,000	psi.

Brinell hardness is 269. Torsion tests on full-sized shafts at the limiting hardnesses are:

	Brinell 225		Brinell 321	
Ultimate strength	128,000	psi.	130,000	psi.
Elastic limit	88,200	psi.	96,500	psi.
Twist at fracture	20°		25°	
Twist at first set	9°		6°	

to distribute weight advantageously results in a cast shaft of lower weight than the forging. In the first place the shaft may be properly counterweighted without having to fasten on separate pieces to balance the part both dynamically as well as statically. The shafts may be ribbed at locations where stresses are highest, with consequent improvement in "fatigue life." The shafts may be economically cored out, lightening the pins and enabling metal to be so distributed about the shaft-center as to make it actually stiffer than a forging while being even lighter.

The last of the copper-bearing alloy steel castings is in the Lincoln Zephyr piston. The carbon is 1.35 to 1.70%, manganese is 0.60 to 1.00%, silicon is 0.90 to 1.30%, copper is 2.50 to 3.00%, and chromium is 0.08 to 0.15%.

Here is a case where fluidity is paramount.

for we make these pistons so that their weight will be no higher than that of equivalent aluminum pistons. The expansion of these steel pistons when hot is less than aluminum and only slightly more than the cylinder bore. This lowered expansion means, of course, less difference between hot and cold compression and less dependence on the piston rings. The steel piston, by its greater strength and hardness, also gives better support to the piston rings with consequent elimination of longitudinal wear in piston ring grooves. As would be expected, the size of the pistons is also maintained much better in service than the aluminum piston, due to a Brinell hardness of 207 to 241 as against 140 maximum in aluminum. One notable effect of this is that the oil consumption of a motor remains constant rather than increasing with continued use.

The substitution of this metal was for another that was also cast, so the novelty here is in the successful production of thin-walled accurate castings of harder metal, the wall as cast being approximately 0.100 in. thick. The inside of the piston is not machined, so that the casting's inside diameter must be within 0.005 in. per side, and the finish weight within ± 2 grams.

Another steel casting is of tungsten-chromium-copper-iron, and is a hard metal used for valve seat inserts. It has 1.20 to 1.40% carbon, 0.30 to 0.50% manganese, 0.30 to 0.60% silicon, 2.50 to 3.50% chromium, 14 to 17% tungsten and 1.50 to 2.00% copper.

This is akin to high speed tool steel, notable for its hardness at red heat and obviously the type of metal required to withstand the exhaust flames around the exhaust valve and yet retain enough hardness to resist the pounding of the valve, even when red hot. It must also have such expansion characteristics that it can be heated in service and after cooling still be tight in the block. Tungsten and chromium are the elements that give the alloy its hot hardness and flame resistance, whereas the tungsten controls the expansion problem. Carbon and copper are required to cast it in a satisfactory manner. Some surfaces of the piece are ground, but since the actual seat is machined, the hardness must be controlled in the range Rockwell C-38 to 46.

Prior to assembly the inserts are cooled in liquid air, they being 0.0035 to 0.004 in. tight before this under-cooling. At liquid air temperature they readily slip into place in the block, and at room temperature or above they are very tight. The use of these inserts has practically eliminated valve grinding.

HEAT TRANSFER

By Curtis C. Snyder

Condensed from "Western Canners & Packers"

THE heat transfer rate of metals is frequently quite important, and there is an erroneous impression that stainless steel is not efficient for cooking operations and others involving the application of heat.

The coefficient of thermal conductivity of metals plays a small part in the ordinary cases of heat transmission from one liquid to another. The term "over-all coefficient of heat transfer" is now accepted as expressing the rate of heat flow from a hot substance to a cold substance when separated by a wall. In a number of service heating installations (condenser tubing, heating coils, heat exchangers) stainless steel has replaced copper, and while the difference in thermal conductivity would suggest a low transference value, the actual efficiency of the unit has been practically the same. This can be attributed to the following factors:

1. Velocity of heating or cooling, and heated and cooled fluids. 2. Nature of material to be heated. 3. Relative temperature of heating and cooling fluids. 4. Thickness of separating wall. 5. Character of surface of separating wall (polish or rough). 6. Surface effects, such as films, deposits, corrosion, color and gas cushions.

In other words, the formation of water or vapor films on metal surfaces, which are always present, have a resistance that offsets advantages that might be expected when using metals with high thermal conductivity. Films on the metal formed by oxidation or corrosion likewise lower the heating efficiency of the unit. Also if the material to be heated does not carry off the heat as fast as it is supplied, little difference will be noted when different metals are used.

A recent investigation conducted at the University of Wisconsin, Department of Dairy Industry — "The Relation of Metals to Heat Transference" — gives the following data:

	Thermal Conductivity	Average Coefficient of Heat Transfer
Aluminum	1450	No value
Aluminum Alloy	No value	98
Copper	2700	95
Tinned Copper	No value	114
Iron	300	No value
Iron Tinned	No value	123
Inconel	102	92
Nickel	406	98
Stainless Steel (18-8) Unpolished	102	100
Stainless Steel (18-8) Polished	No value	98

Conclusions are drawn from the above that the heating efficiency of stainless steel and other competitive metals are practically the same.

A MAN OF METALS

Charles Morris Johnson

He worked in 1917 on the problem of "producing a steel that could be forged, rolled or sheared in thicknesses of 0.01 to 1 in. or more and offering a maximum resistance to attack by oxy-acetylene flame." The research resulted in a series of high chromium-nickel steels containing silicon, first exhibited in 1920 before the Amercan Society for Steel Treating

WHEREVER steel is analyzed today the hand of Charles Morris Johnson may be felt. Directly or indirectly, all steel laboratories use procedures either devised or perfected by him. This is especially true of control analyses for the melting of alloy and tool steels. This fact alone may justify tribute to any man in our modern industry, but Charles Morris Johnson has not been satisfied to be an analytical chemist of international renown. He has also taken such a hand in the compounding of mixes and the direction of processes that he emerges equally brilliantly as the originator of an important class of non-corrosive and heat resistant alloys. Such is the picture we would paint of a man equally skilled in the building up and in the tearing apart of alloy steels.

He was born in Alliance, Ohio, but at an early age his parents, Rev. and Mrs. George W. Johnson, moved to Pittsburgh. When only 20 he received his Bachelor of Philosophy degree in the scientific course, so called, from Western University, the parent school from which has sprung the University of Pittsburgh. This institution later conferred upon him the degree of Master of Philosophy in recognition of his work in the advancement of the steel industry.

In 1898 he married Mary Alma Yost, a talented musician, composer and teacher. There are five children, two boys and three girls — and in 1936 four grandchildren.

Upon graduation he accepted employment as assistant chemist in the laboratory of Park, Brother & Co. at Pittsburgh, one of the world's largest manufacturers of crucible steels and then the largest in America. In 1900 Johnson became chief chemist for the steel mill as well as its plumbago crucible factory. In 1901 Park, Brother & Co. became part of the newly formed Crucible Steel Co. of America. Johnson continued in his position of chief chemist and today still holds the same post. In 1918 he was appointed director of research for the Crucible Steel Co., which position he held for some years until this important work was transferred to another locality. Simple arithmetic can show, therefore, that Charles Morris Johnson is short only three years of having spent a half century of useful endeavor in one locality.

A record of his progress may be read in his publications and patents. These are too numerous to list here, but for the sake of the record are printed as a footnote. They began to appear in 1905, in the *Journal* of the American Chemical Society under such titles as "Rapid Determination of Nickel in the Presence of Iron, Chromium and Manganese," "Determination of Carbon in Iron and Steel by Direct Combustion and With Red Lead or Litharge." These articles made chemical and metallurgical history. The fundamental methods and their adaptations have become so common-place that we are now apt to slight their development unless we are willing to relax and imagine the difficulties we would have today without these necessary refinements. In 1908 Johnson published the first edition of the "Chemical Analysis of Special Steels, Ferro-Alloys and Graphite." This is the work which has become the steel analyst's Bible. Now in its fourth edition, it stands as a crowning work destined to serve for many years to come. Work on it has been unceasing; for the past year an investigation has been underway on the analysis of various stainless grades with perchloric acid.

Later we find a transfer of interest to the special and alloy steels. Such papers as "Alloy Steels of High Elastic Limit, Their Heat Treatment and Microstructure" appeared in *Transactions* of the American Society for Steel Treating, 1922, and "Corrosion Data on Various Alloys and Alloy Steels" in *Proceedings* of the American Society for Testing Materials, 1924. Recently he contributed three sections to Collier's New Encyclopedia covering the subjects of Crucible Steels, Silicon Steels and High Nickel Steels. He is also the author of the section on "The Rezistals" in Thum's Book of Stainless Steels, published by the A.S.M. in 1933.

We might judge from the bibliography that Johnson has devoted himself to writing. Such is far from the case. In 1908 he began the manufacture of his own designs and compositions of laboratory refractories, such as combustion tubes, boats, and muffles, making in 1913 the first tapered outlet combustion tube. A department at Park Works making such ware is still operating under his supervision.

In 1909 and 1910 he was granted a series of four patents covering the manufacture of metallic tungsten powder for use in melting high

speed steel in the crucible. A factory was equipped at 51st and Butler St., in Pittsburgh, where during the World War as much as 100 tons of metallic tungsten per month was produced. As the electric furnace gradually replaced the crucible process for melting tool steels, ferrotungsten replaced the metallic powder as a source of the alloying element, so this plant became inactive in 1925. At this same place, in 1914, Johnson produced uranium oxide, commercially free from vanadium, for use in the manufacture of uranium high speed steels which were then enjoying a brief period of popularity.

Despite the intense activity at Park Works during the War, with the added responsibilities at the crucible factory and the tungsten plant, he found time in 1917 to start an intensive investigation of the problem of producing a steel that could be forged, rolled or sheared in thicknesses of 0.01 to 1 in. or more and offering a maximum resistance to attack by oxy-acetylene flame. The result was a series of patents granted in the period of 1920 to 1922 covering steel alloys, vault plate steel, high speed steels with molybdenum and high vanadium as well as certain high nickel-silicon-chromium steels for heat and corrosion resistance. These latter are now known as the "Rezistal" steels. They were first exhibited at the Philadelphia convention of the American Society for Steel Treating in the fall of 1920. In 1920 crucible melting still predominated for high alloy steels, and for this reason the carbon content in these early rezistals ranged from 0.25 to 0.45%. Present grades usually carry a maximum of 0.15 or 0.20% carbon, and are essentially high chromium-nickel steels with 1 to 4% of silicon added as required to establish unique properties. The creation of these alloys entitles Charles Morris Johnson to acclaim as a fellow investigator with Marsh, Haynes, Strauss, Maurer, Brearley, Becket, and Armstrong.

In 1918 Johnson was elected a Fellow of the American Association for the Advancement of Science, and in 1935 a member of the national research organization known as the Society of Sigma Xi "in recognition of his contributions to the chemistry of steel analysis, control and manufacture." He is one of the outstanding members of the American Society for Metals. He was one of the first to realize in the early days of the Detroit and Chicago groups that no reason existed for rivalry. He lent his influence toward the plan of alternating the meetings in Pittsburgh (one month the Detroit Chapter and the next month the Chicago Chapter would meet) and in this way he was probably the originator of unification ideas which later led others to form the amalgamated society. He certainly is one of the most faithful members of the Pittsburgh Chapter, ever active in all branches of its diversified yearly program. Always serious in appearance, he has, however, the keenest sense of humor a man can possess, together with a dry wit so subtle that only those intimately acquainted with him can appreciate its mastery.

Surely we honor ourselves in expressing this feeble tribute to our esteemed fellow member, Charles Morris Johnson.

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Treatment of Ores. Patent No. 964870, Jan. 1910.

Furnace for Reducing Metallic Oxids. Patent No. 964871, Feb. 1910.

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Method for Determining Phosphorus in Non-Vanadium Steels and Pig Iron Using a Faintly Ammoniacal Water Solution of Ammonium Molybdate. J. Ind. Eng. Chem., v. XI, No. 2, 1919, p. 115.

(List concluded on page 74)

RADIOGRAPHY OF METAL

in principle

and practice

By Kent R. Van Horn
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Aluminum Research Laboratories
Cleveland, Ohio

X-RAYS are a form of radiant energy or electromagnetic waves which were first detected by Roentgen in 1895, and are frequently called Roentgen rays in honor of the discoverer. The latter name is used in Germany, while the term X-ray is more prevalent in France, England, and the United States.

X-rays are similar in many respects to light and other radiation of the electromagnetic spectrum, in that they travel in straight lines, traverse through space without transference or intervention of matter, affect a photographic film, and are not influenced by either electrical or magnetic fields. The various electromagnetic vibrations differ essentially in wave length, the gamma rays emitted during the disintegration of radioactive elements are the shortest (with the exception of "cosmic rays," whose nature is controversial), then the X-rays, followed by the ultra violet, the visible, then the infra-red or heat rays, solar radiation, radio and finally the extremely long waves of electricity. Generally the shorter wave lengths are less absorbed by intervening matter and are consequently more penetrating. Gamma rays emanating from radium or its associates, having a wave length of from 0.005 to 1.4 Å (1 Å = 10^{-8} cm.), and X-rays, ranging from 0.06 to 1019 Å, penetrate material which is opaque to visible light having a wave length of from 3800 to 7700 Å.

Light is transmitted through different types of glass with varying degrees of ease. Similarly, X-radiation is absorbed differently by various substances of greater or less density; that is, all materials do not possess the same degree of X-ray transparency. The absorption coefficient of X-rays is roughly proportional to the atomic density of the absorbing medium. Consequently a sound section of steel will absorb more radiation than a similar section of aluminum or organic tissue. With X-rays it is possible, therefore, to locate inclusions differing appreciably in density from the surrounding material. These relations are the basis of the expanding science of radiography, which may be defined as the non-destructive testing of matter with radiant energy (either X-rays or gamma rays). The experimental procedure consists of passing radiation through the specimen and detecting the various intensities of the emergent beam by a photographic film or fluoroscope screen.

Probably the first practical application of X-rays was radiography, and today it is an invaluable test for medical and industrial diagnosticians. In 1928, X-ray tubes rated at 200,000 volts peak were available which could penetrate 3 in. of steel. This has been increased to 5 in.

Extracts (without references) from an article for next Edition of A S Metals Handbook

of steel with 400,000 v. peak apparatus in 1935. Reasonable quantities of gamma rays of shorter wave length can penetrate 10 in. of steel. The present article will be confined to X-ray radiography because of its advantages for laboratory or shop inspection of moderate thicknesses of metal ordinarily met in industry. However, much of the individual discussion of general technique and interpretation apply to the gamma ray.

Generation of X-rays and Apparatus

It is known that X-rays are produced when matter is bombarded by a rapidly moving stream of negatively charged particles (electrons) — that is, when the electrons are suddenly stopped by matter the kinetic energy is converted to energy of radiation. In addition, the absorption of X-rays by various materials is accompanied by the emission of secondary radiation. The essential conditions for the generation of X-rays are:

(1) Source of electrons (cathode rays) proceeding toward the target.

(2) A target or anode located in the path of the cathode rays.

(3) A means of applying a potential difference between the cathode and the target which will give the requisite velocity to the electrons during the passage of the intervening space, so that when they bombard the target the necessary X-rays will be propagated.

The first two requirements are incorporated in the X-ray tube. This may be of two types, although the electron type is universal for industrial radiography. It is a highly evacuated glass bulb or cylinder containing a tungsten wire filament which emits the cathode rays, and either a solid or plate target, and may range in capacity from 85,000 to 400,000 v. peak. The lower voltage tubes have a fine focus and are generally air cooled, while water cooling and larger focal areas are characteristic of high voltage tubes. Their general construction was described by Coolidge and Charlton in METAL PROGRESS, Nov., 1933.

The third condition, a difference in potential, was obtained for the original apparatus by a direct current electrostatic generator. However, the high tension, alternating current closed core transformer is used today for industrial installation. Accessory equipment for the transformer type of power consists of the following:

(1) An auto transformer for the control of the high tension transformer input. (2) A means of current rectification from alternating to direct current, either valve tube or mechanical. The valve tubes or kenetrons are now rapidly replacing the older mechanical rectifiers. (3) A device for regulating tube current. (4) Separate transformers for supplying the filament current of the X-ray and valve tubes. Additional windings on the high tension transformer or insulated storage batteries are also satisfactory. (5) Instruments for measuring voltage such as a calibrated primary transformer voltmeter, sphere gap or spectrometer, or electrostatic voltmeter.

Radiographic units may be classed according to portability: (1) Permanent type, where the location of the apparatus is fixed; (2) flexible type of equipment that may be moved throughout the plant with comparative ease. The more recent installations are generally portable and very compact; an oil immersed power plant and X-ray tube can be contained in a shock-proof case 6x4x4½ ft. suspended on trunnions on a movable truck. It is imperative to protect the operators or any persons in the vicinity of all types of apparatus, from the injurious effects of both primary and secondary radiation. This is accomplished by suitable thicknesses of dense materials which are impervious to X-rays (lead or concrete) and fencing off a generous area around the temporary location of a portable set.

Methods of Detecting X-rays

X-rays are detected by their effects on matter, rendered visible either temporarily or permanently. In addition, X-rays are revealed by induced physical and chemical changes which may be made permanent. Thus X-rays have been detected by an ionization chamber, fluorescent screen, photographic film, plate or paper. Inasmuch as the film is generally used for industrial radiography, the other methods will not be discussed.

An X-ray paper is marketed which costs about half that of a film and differs in several significant characteristics. The contrast of the paper is 40% less than the film, and the range of useful densities or latitude is also materially less because of the reflection of some light from the surface. However, X-ray paper may be satisfactory for special cases where previous examination of a large number of similar parts had indicated that the objectionable defects would be adequately disclosed.

Light rays, X-rays and gamma rays produce a latent image on a photographic emulsion which is permanent and reproducible. "Dupletized" films designed especially for X-ray service have two very thick sensitive layers, one on each sur-

face. This produces more contrast than a single emulsion. The image registered on the negative is dependent on the variations in absorption of the X-rays by the object and on the characteristics of the silver bromide emulsion.

The important qualities of films are contrast, latitude, and speed. As the exposures for industrial radiography are relatively long, compared to medical work, the speed encountered in the films of today does not vary enough to warrant consideration. The radiographic sensitivity (the minimum variation in thickness, or density detectable in a specimen) is greatest with high contrast emulsions. However, with maximum differentiation of detail (contrast), the range of useful film intensities (latitude) is diminished.

In other words, contrast will reveal minute defects in a certain section but would sacrifice adequate exposure of regions of appreciably greater or less thickness. Sufficient latitude will allow for unavoidable variations in exposure and development, also reasonable differences in thickness. Generally, emulsions that possess a compromise of contrast and latitude are desirable, although for some conditions requiring extraordinary sensitivity, high contrast may be selected.

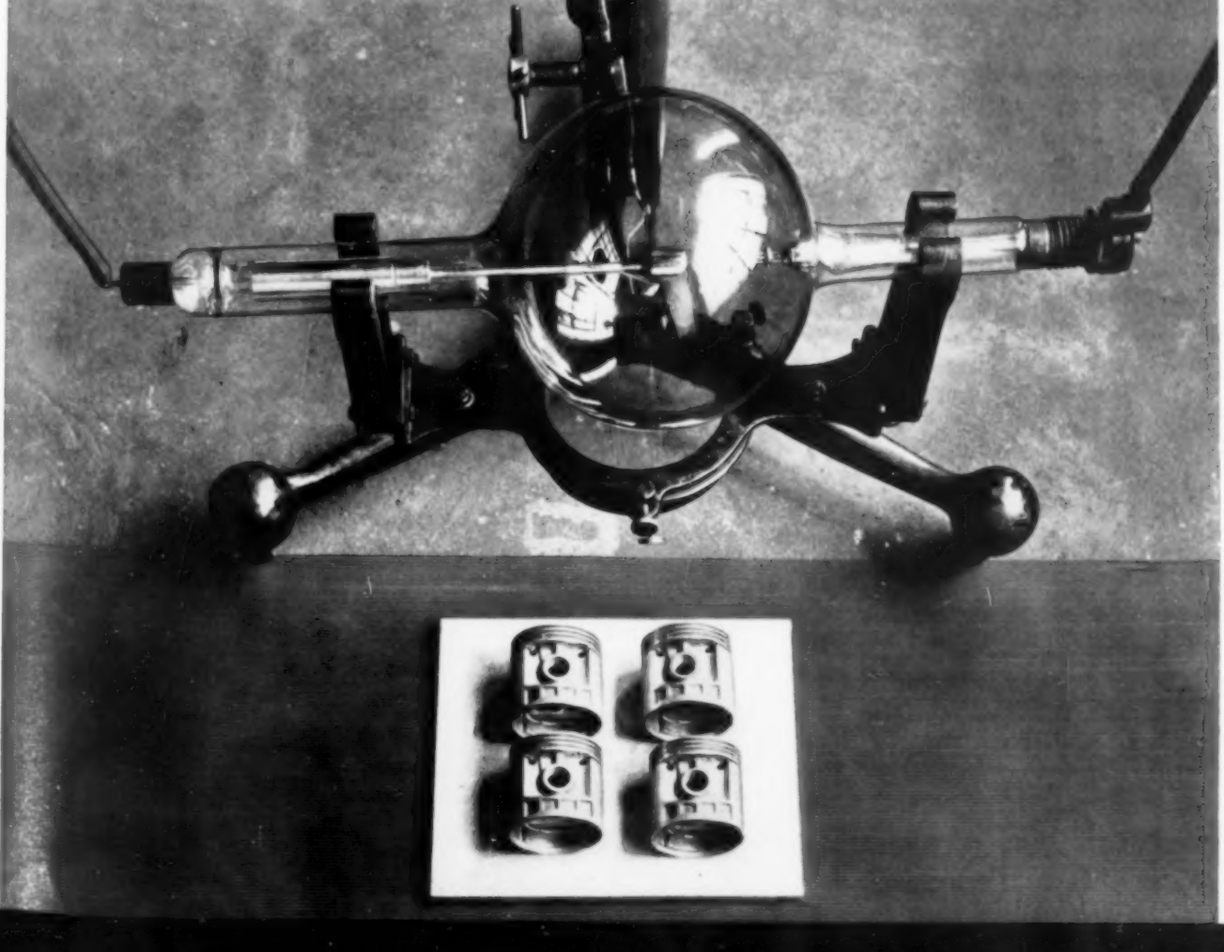
Films are developed and fixed by the tank method, in solutions designed to give extreme contrast and negligible chemical fog, wherein contrast is sensibly maximum in from 5 to 9 min. at 65° F. As the density (film blackening) increases with developing time, the exposure may be reduced by prolonging the latter. Thus, with an 8-min. development, the exposure may be decreased by 30% of that required for a 5-min. period.

Negatives should be viewed for interpretation with a source of diffuse illumination which will reveal detail in areas of extreme blackening. The density of the film does not affect the visual sensitivity with a variation in illumination ranging from 5 to 3000 foot-candles. About 1000 foot-candles are recommended; this is obtained with either the 200 or 250-watt blue lamps that are supplied in the commercial illuminators.

Film blackening may be precisely measured by a micro-photometer. A density difference of 2% is considered the standard minimum value of detection.

Improvement in contrast and a decided reduction of exposure time can be obtained by employing intensifying screens. A screen consists of an intensifying compound, usually calcium tungstate and infrequently zinc silicate, or zinc sulphide or barium platino-cyanide, coated with a cellulose binder on cardboard. On exposure to X-rays or gamma rays, a visible and blue violet light is emitted from these screens to which a film emulsion is highly sensitive. Two screens, one in front and the other behind the film are

Set-Up for Radiography, Viewed From Above. Tube rests on tripod; below are four cast pistons placed on a light-tight package containing film and intensifying screens



generally used, although superior definition but less speed is procured with only one. Intensifying screens maintained at low temperatures are extremely fast, as exposures at 40° F. are 33⅓% less than at 70° F.

Metal foils, particularly lead, and sometimes copper or aluminum, slightly decrease the exposure period and improve the quality of the negative. Two lead foil filters about 0.005 in. thick, one on each side of the film will reduce fogging by absorbing some of the secondary radiation. The definition is also enhanced by the resulting fine grained image.

Intensifying screens must be handled carefully as they are brittle, expensive, and scratch easily. Dirt or blemishes on the sensitive surface are readily recorded on the negatives and complicate the interpretation.

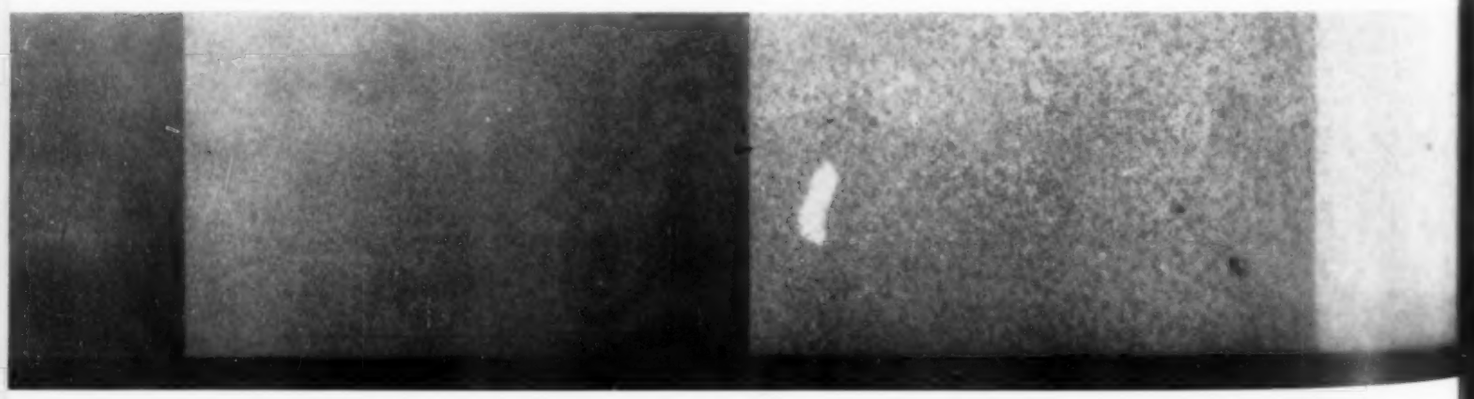
Sensitivity; General Technique

The minimum variation in density within a specimen that is perceptible is a measure of the overall accuracy of the radiographic method. This sensitivity may be expressed as the smallest thickness of defect in inches that is revealed on the radiograph, or as the percentage of the total thickness examined which the smallest defect detectable represents on the radiograph. Of the factors that affect sensitivity, some may be controlled, while others are permanent limitations imposed by the apparatus.

The type of target of the X-ray tube, the material supporting the target, the size of the focal spot, and the method of rectification influence the sensitivity and cannot be altered in a particular arrangement of equipment. The higher the atomic number of the target metal, the more penetrating and shorter the wave length, although this is accompanied by decreased contrast. If the target is not solid metal but a button imbedded in a supporting conductive metal, extraneous radiation of different wave lengths may also be emanated from the surrounding metal. This may approach 10% of the total if not removed by proper filters. The focus of the X-ray tube is not a point, but occupies a fixed area. Consequently, the smaller the focal area the better the definition and the less the distortion. Rectification units of the same peak kilovolt capacity have dissimilar wave length distributions and mean voltages, thereby generating different proportions of long and short wave lengths.

Among the important factors affecting sensitivity which can be regulated is the quality of the radiant energy. The radiation emitted from the tungsten targets generally used varies over a considerable range of wave lengths related to the voltage applied. As the potential increases from about 89,000 to 200,000 v. peak the wave length of maximum intensity decreases from 1.35 to 0.063Å with a corresponding reduction in contrast and sensitivity. However, the shorter and more penetrating wave lengths are required for thick samples. Consequently, it is desirable to employ the lowest potential which will penetrate a given thickness and affect the film in reasonable time. Exposure charts for various thicknesses of metals under different conditions are available. However, these data may not apply to all apparatus because of the difficulty in reproducing radiation with a pulsating potential and variations in films and screens.

Sensitivity is dependent on the wave length of the X-rays and the nature of the exposed matter (excluding the fogging effect produced by



Part of a Radiograph of Step-Casting Used to Check Exposures. In this case the aluminum alloy casting was immersed in carbon tetrachloride to increase the definition; if it had not, the thinnest step at left would have been indistinguishable from the background. Mottling is general porosity in the heavier sections, dark spots are shrinkage, white area is segregated copper or iron compound

scattered or secondary radiation). Secondary radiation consists of primary X-rays that are scattered through wide angles with no change in wave length, and ejected electrons which propagate X-rays of longer wave length characteristic of the absorbing substance. The quantity of secondary radiation increases with the applied voltage and the number of atoms encountered — that is, the thickness of the material. The secondary energy derived from the specimen and surrounding objects fogs the film, thereby diminishing the sensitivity. Fortunately this may be materially reduced by the use of Potter-Bucky diaphragms, lead or copper screens, and other expedients.

The geometrical relations of the focus of the X-ray tube to the film, the location, the size and orientation of defects also influence the sensitivity of radiography. Although the focal area is permanent, definition can be improved by increasing the tube-to-film distance. The greater the distance, the smaller the angle of exposure and the better the definition or sharpness. This relation is limited because of the corresponding increase in exposure time since the intensity of X-rays or gamma rays decreases inversely as the square of the distance from the source.

Flaws may occur in any part of the specimen and may be oriented at any angle. As the defect-to-film distance is increased, or the diameter of the defect is decreased below one inch, the actual sensitivity is proportionately diminished. The orientation of minute cracks is important and may necessitate several exposures at different angles so that cracks presenting too small a variation in thickness for detection in one direction may be revealed in another.

It follows from the discussion of the various factors that the best sensitivity will result from employing a small focus tube, a low voltage, large tube-to-film distance, high contrast film exposed with intensifying screens, and with the scattered radiation and chemical fogging reduced to a minimum. Sensitivity data are given in the table and indicate the smallest detectable difference in thickness that may be obtained parallel to the path of the X-radiation. The practical significance is that variations of composition or thickness causing less change in film density than the per cent sensitivity for a certain thickness of sample will probably escape detection.

Interpretation of Radiographs

A radiograph is a shadow picture of material more or less transparent to radiation. The X-rays darken the film so that regions of lower density which readily permit penetration appear dark on the negative in comparison with areas of higher density which absorb more of the radiation. Thus, voids and cavities in metals are recorded as darker areas, while heavy inclusions, such as iron scale or copper segregation in an aluminum alloy, register a corresponding lighter region on the radiograph. The sensitivity values indicate the smallest variation in absorption that can be appreciated.

In the metal industry, most of the radiographic installations are located in the foundry and the welding shops. In castings, differences in thickness due to the form and intentional cavities, as cored holes, are regions of low density and are revealed as darkened areas. Specimens containing variations in thickness caused by the unintentional absence of metal are also more transparent, resulting in darkening of the film. The common casting defects of the latter type may be recognized on the negative by the following characteristics:

1. Gas cavities, blow holes and minute gas porosity appear as well defined spherical or rounded darkened areas.

2. Shrinkage, pipe and shrinkage porosity are represented by filamentary or dentritic dark regions of irregular dimensions and indistinct outline.

3. Misruns appear as very prominent darkened areas of variable dimensions with definite, smooth outlines where the metal has failed to fill.

4. Sand inclusions occur as gray to black spots of an uneven or granular texture with indistinct extremities.

5. Cracks are represented by darkened lines of variable width and are filamentary when derived from insufficient feeding or contraction (shrinkage) on cooling from the melt. Cracks originating from internal stress in solid metal are either angular or straight and are of more constant width.

Sensitivity of Radiography on Steel

	Thickness of Sample				
	3/4 in.	1 in.	1 1/2 in.	2 in.	3 to 5 in.
Best laboratory work					
150,000 V. peak	0.0039 in.	0.0041 in.	—	—	—
200,000 V. peak	0.0049 in.	0.0052 in.	0.0057 in.	0.0063 in.	—
Industrial work					
200,000 V. peak	0.8 to 1%		1 to 1.5 %		2 %

6. Inclusions such as foreign material, segregation, oxide and slag in steel castings generally appear as dark regions of definite and smooth outline. In light alloy castings, copper or iron segregation and foreign matter of greater density than the base metal occur as well defined, white areas opaque to the X-ray.

Radiography of steel welds is confined primarily to boilers, pressure vessels and pipe. The origin and interpretation of flaws have been exhaustively studied during the standardization of inspection methods. The defects in order of prevalence of occurrence in steel welds are: (1) Slag inclusions, (2) porosity, (3) cracks, (4) incomplete fusion between the weld and base metal or between two layers of weld metal. All the imperfections are less dense than steel and are recorded as darkened regions on the radiograph. With the exception of incomplete fusion, which is represented by a dark line parallel to the scarf of rather constant width and direction, the defects are similar in appearance to their description for sand castings.

Radiographic Applications

In the metal industries, radiography has been largely restricted to the inspection of cast or welded products. Some forgings have revealed internal cracks, laminations and inclusions, but the occurrence is too infrequent to warrant serious consideration of the X-ray as a means of routine inspection.

Apparatus has been installed in four types of organizations: (1) Foundries for the inspection of castings and ingots, (2) manufacturers of boilers or pressure vessels for the testing of welds, (3) government arsenals, consulting laboratories and universities for the examination of castings, welds and miscellaneous products, (4) companies fabricating miscellaneous non-metallic products.

The first radiographic equipment exclusively for the study of foundry products and technique was installed in this country in 1927 in the Cleveland, Ohio, foundry of the Aluminum Co. of America. Each year has added to the list of companies which have found the X-ray method to be indispensable for the inspection of castings. Apparatus now exists in cast or alloy iron, steel, and light alloy foundries, and is used in eight or nine out of ten times for the development of casting technique, and only about one in ten for routine inspection. After a successful procedure has been established only occasional X-ray confirmation is necessary. However, complete examination is warranted for highly stressed castings such as pipe or fittings for high pressure-temperature systems, heat resisting retorts and airplane crank cases or shock absorbers.

An outstanding application was the non-destructive testing of all pipe, fittings, and turbine shells for a 1200-lb. steam line of a large electric power plant. After several years of service, no casting has failed, although a considerable number were originally rejected because of the X-ray specifications. Frequently, when the production of a part is too small to justify the expense of a forging die and operation, castings, proved by the X-ray to be homogeneous and sound, have been acceptable. A manufacturer has appreciably increased the service life of heat resisting furnace fittings, pots, retorts, and thermal protection tubes by making sure that no dangerous sub-surface defects exist in the castings shipped. Some indication of the value of radiography to this producer is that 1,450,000 sq.in. of film were exposed in the year 1935.

The ability of the X-ray to disclose the injurious defects in welds has been recognized by the Bureau of Engineering of the U. S. Navy, the American Society for Mechanical Engineers, and the American Petroleum Institute. In 1931, the A.S.M.E. boiler code governing boiler drums and unfired pressure vessels permitted welded construction but required complete X-ray inspection of the seams. Welded construction of pressure equipment has progressed phenomenally since 1931, although little utilized previously because an efficient non-destructive test had not been available. Also, it is doubtful if the fusion welded structures would have attained their popularity without the confidence reflected by the acceptance of welded boilers.

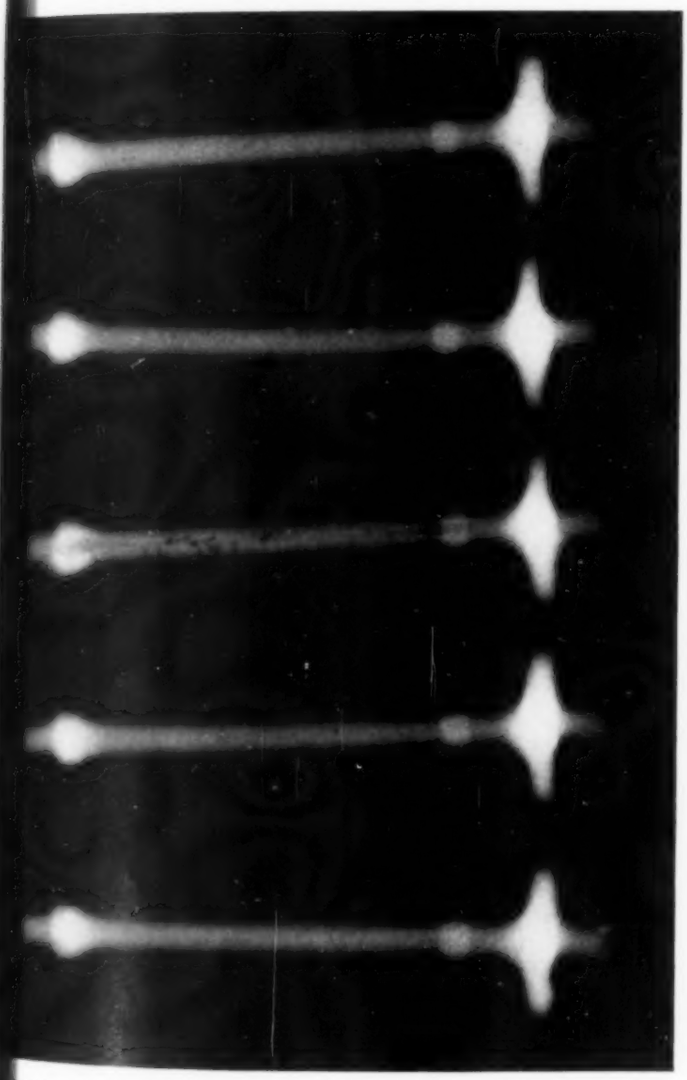
In 1936, there are 48 equipments distributed among 34 companies interested in boilers and pressure drums. The eleven major companies, engaged in fabrication of pressure apparatus, have examined, to date, over 7000 vessels representing approximately 150 linear miles of welded steel joints ranging in thickness from ¼ in. to 4⅞ in. All fusion welding of the penstocks of the power plant at Boulder Dam, totaling 75 miles of seam, is minutely inspected. This project alone will require about 159,000 exposures consuming 24,000,000 sq.in. of film. Unlike in the foundry, the majority of the weld radiography is devoted to routine testing.

U. S. Army officials, visualizing the possibilities, installed the first equipment in this country for the radiography of cast and welded prod-

ucts in 1922 at Watertown Arsenal. This was followed by Rock Island Arsenal; it also interested other governmental divisions. The consulting laboratories and some universities have materially aided in the development of X-ray technique and the introducing of new applications. The experience of these organizations includes castings, welds, and non-metallics.

Gamma Ray Radiography

Gamma rays emanated from the disintegration of radioactive elements have experienced only limited radiographic applications. The source may be radium, radon, or meso-thorium, which emit considerably shorter and more penetrating wave length radiation than the X-rays. It is estimated that the gamma wave length spectrum corresponds to X-rays that would be generated by potential of from 400,000 to 1,500,000 volts peak.



Radiographs of Four Sound and One Defective Steel Castings

In addition, the gamma radiation differs from the X-rays in several pertinent qualities. As contrast diminishes with decreasing wave length or increasing voltage, the gamma rays are unable to reveal the very small defects. The gamma wave lengths are characteristic of the source and cannot be regulated for contrast or variable thickness. An advantage of the gamma radiation which improves the sensitivity is the small absorption and low scattering power resulting in appreciably less fogging than that produced by X-rays. The net effect of the two compensating factors, lack of scattering and low contrast, is that the sensitivity of the gamma ray is inferior to the X-ray for material penetrable by the latter. The sensitivity of gamma rays under laboratory conditions for ½ to 2 in. of steel ranges from 5 to 1.75% and for 3 to 6 in. is 1.3%.

Other important considerations which prevent gamma radiation from competing with the X-ray are the expense and time of testing. The rental of 100 mg. of radium is about $10 per day and would require up to 24 hr. exposures for thick steel. Although gamma rays are not directional but are emanated spherically so that many specimens may be simultaneously examined by suitable distribution about the source, the number of exposures for a specific time is relatively small compared to the large number that could be obtained with the X-ray in the same period.

The gamma radiation is attractive because of the good definition, absence of machinery and ease of arranging exposures. Excellent definition can be procured by decreasing the dimensions of the source, that is, by reducing the quantity of radium or absorption of radon by a small piece of carbon. The simplicity of gamma ray technique is utilized for the radiography of steel castings and welded structures in an assembly or in service where it is inaccessible to X-ray apparatus. Frequently circumferential welds of large pipe made in the field are more economically examined by gamma radiation because one complete joint may be simultaneously exposed from a single radioactive source. Also, companies not having sufficient non-destructive testing to justify an expenditure for an X-ray installation, rent radium on occasion. It would seem that the gamma rays will not be used extensively for industrial radiography, but will be confined primarily to the examination of material opaque to the X-ray (say 5 to 10 in. of steel) or inaccessible to the latter type of radiation.

VERTICAL FURNACES

for hardening,

for tempering

By F. E. Harris
Furnace Engineer
Buick Motor Car Co.
Flint, Mich.

AMONG the great variety of industrial heating applications, where special problems of production and layout are to be met, it is frequently difficult to find enough floor space for the necessary furnaces. In such cases the upright conveyor type of furnace may often present the most convenient solution. It will be the intention of this article to deal with the design features of this type of equipment, showing two applications of the many which have been made in the main plant of Buick Motor Car Co., Flint, Mich., and to point out its advantages and (on the other hand) its limitations.

As in most continuous heating equipment, each application should be studied as a special problem. The major variables of this problem are the size and shape of the pieces to be heated, the requirements for surface protection, the production desired, the temperatures which must be attained, and the handling problems imposed by the desired location in the shop and the operations preceding or following the heating cycle.

In other words, the field for vertical furnaces for heat treating operations will be certain special and particular applications rather than the ordinary field well served by the more or less standardized furnaces made by several reputable builders for general duty. Widths, heights, conveyor arrangements, zoning, loading and unloading details will vary with practically every application. A general description such as this can cover only the fundamental points of design.

A very common and satisfactory use is found in the low temperature field of drawing operations, from 400° F. to 1000° F., on parts such as transmission gears, flywheel ring gears, coil and leaf springs, spline shafts, rear axle shafts, and other parts of relatively small weight. These applications are similar in that all the stock is cooled to room temperature after heating on the endless conveyor and before unloading, either for ease in handling or to prevent scale or rust from forming on the finished parts.

In the vertical furnace loading and unloading is done at one point or station, with the conveyor trays in the open and at a convenient height for handling. For all such low temperature operations, the heat application, its control by baffling, and the general construction of frame, conveyor and brickwork will be similar. This general class will now be described, taking as a specific illustration a duplex furnace for drawing coil springs for front wheel suspensions, as shown in the general drawing on page 54.

Simplicity of temperature control and fuel economy are predominant features. Dual combustion boxes (really they are thick-walled tubes of refractory, with longitudinal slot for discharge

of hot gases) are fired from either side, and are located centrally at the lower part of the shaft. A steel baffle extends upward and divides the furnace into two "legs," one of which on the loading side is the "ascending leg" for the stock to be heated, the other the "descending leg" for the stock to soak at the desired temperature.

The combustion gases, entering the furnace through the narrow longitudinal slots in the combustion boxes, travel upwards, against the descending stock, across on top and then down the other side of the baffle, leaving the furnace at the bottom of the charging side and being carried out of the shop by a properly placed hood. Thus, all gas flow is counter to the work being heated, and the temperature of waste products of combustion is relatively low as they leave the furnace.

These refractory lined combustion boxes are each supplied with a duplicate set of gas burners, the larger of which is automatically controlled from a thermocouple at the top of the furnace. The small burner fires continually and serves to keep the combustion box hot, without having the capacity to hold the furnace at the temperature desired. The large burner is on or off as required by the temperature control.

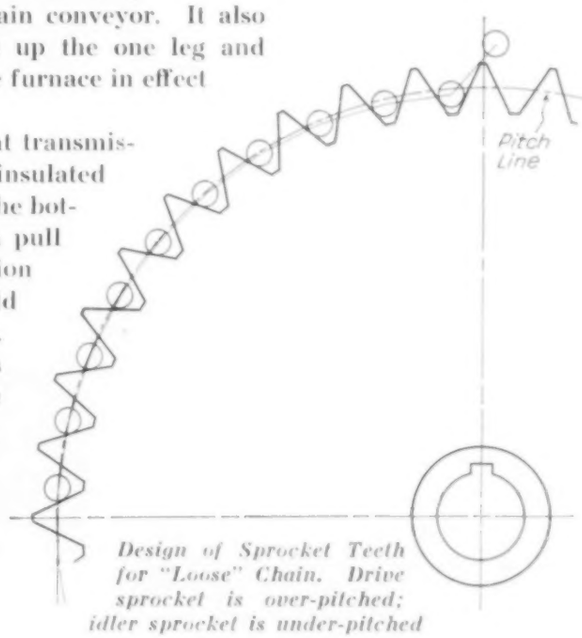
These two comparatively small boxes afford complete combustion for the gas-air mixtures supplied through the burners. Furthermore, they will operate under a considerable back pressure, which is an essential point, as no venting from the top of the furnace shaft is allowable, with its subsequent suction from natural draft. The thin steel baffle radiates heat rapidly from the hot ascending gases into the cold charge as it is carried upward by the chain conveyor. It also serves to direct the gases up the one leg and down the other, making the furnace in effect a two-zone construction.

The mechanism of heat transmission is as follows: The insulated chamber or shaft, open at the bottom of both legs, affords a pull on the products of combustion only as the gases on the cold side in cooling are heavier. This natural flow assures the definite travel of the gases, without undue chimney effect or channelling. The hot gases issuing from the combustion boxes are directed against the central steel baffle, in a thin stream distributed across the width of the furnace. These hot gases travel along the vertical baffle, affecting immediately the thermocouple located at the top of this leg, and serve to hold the stock at temperature. These gases, descending, will maintain the correct travel for uniform heating regardless of the furnace width since the greatest volume of gases will flow through the coldest channels. This automatically compensates for non-uniform loading and radiation.

With proper speed of the conveyor in relation to its load and the temperature employed, two-zone heating is therefore attained accurately and uniformly with one control couple and one source of heat. The two zones are *(a)* holding on the descending leg and *(b)* heating on the ascending leg.

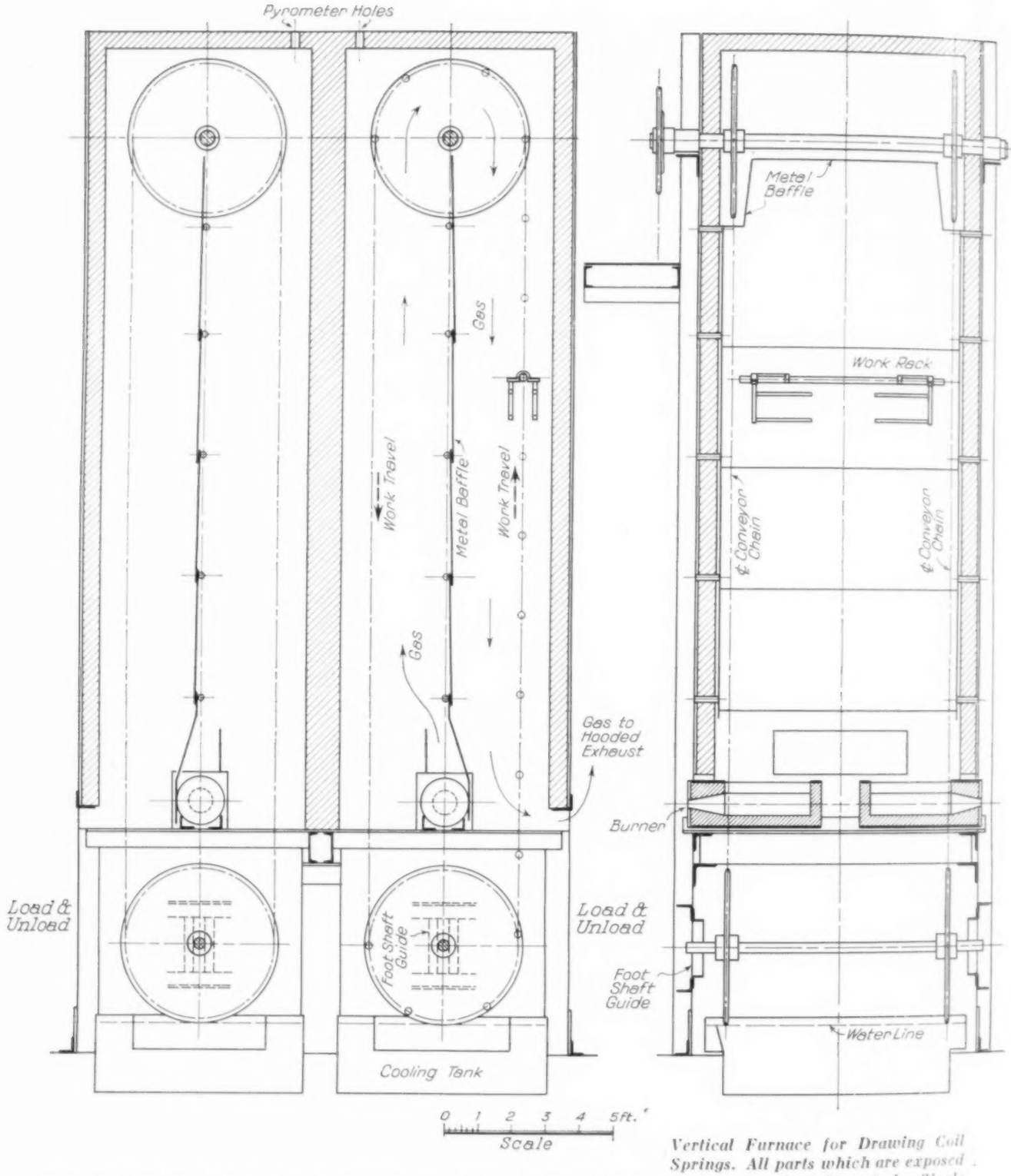
The frame construction and brick lining are relatively simple. The upright structure is entirely open except for its steel supporting legs for the first 6 ft. or so; this allows convenient loading and unloading spaces. A single layer of insulating brick is placed against the outer steel casing to form the vertical sides and ends; insulating covers tightly seal the top. The bottom, entirely open, allows free travel of the conveyor and its load, in and out, while the only openings in the straight walls are in the sides — one for the combustion boxes at the bottom, and one at the top for the conveyor head shaft. This makes for easy construction and maintenance, and prevents any leakage of combustion gas or infiltration of outside air.

For such low temperature work, the endless conveyor is made of plain carbon steel throughout. It is driven through sprockets on the head shaft. This shaft carries the entire load, through two strands of chain, connected with suitable crossbars for load-carrying fixtures. The lower or foot shaft floats on the loop of conveyor chains.



Design of Sprocket Teeth for "Loose" Chain. Drive sprocket is over-pitched; idler sprocket is under-pitched

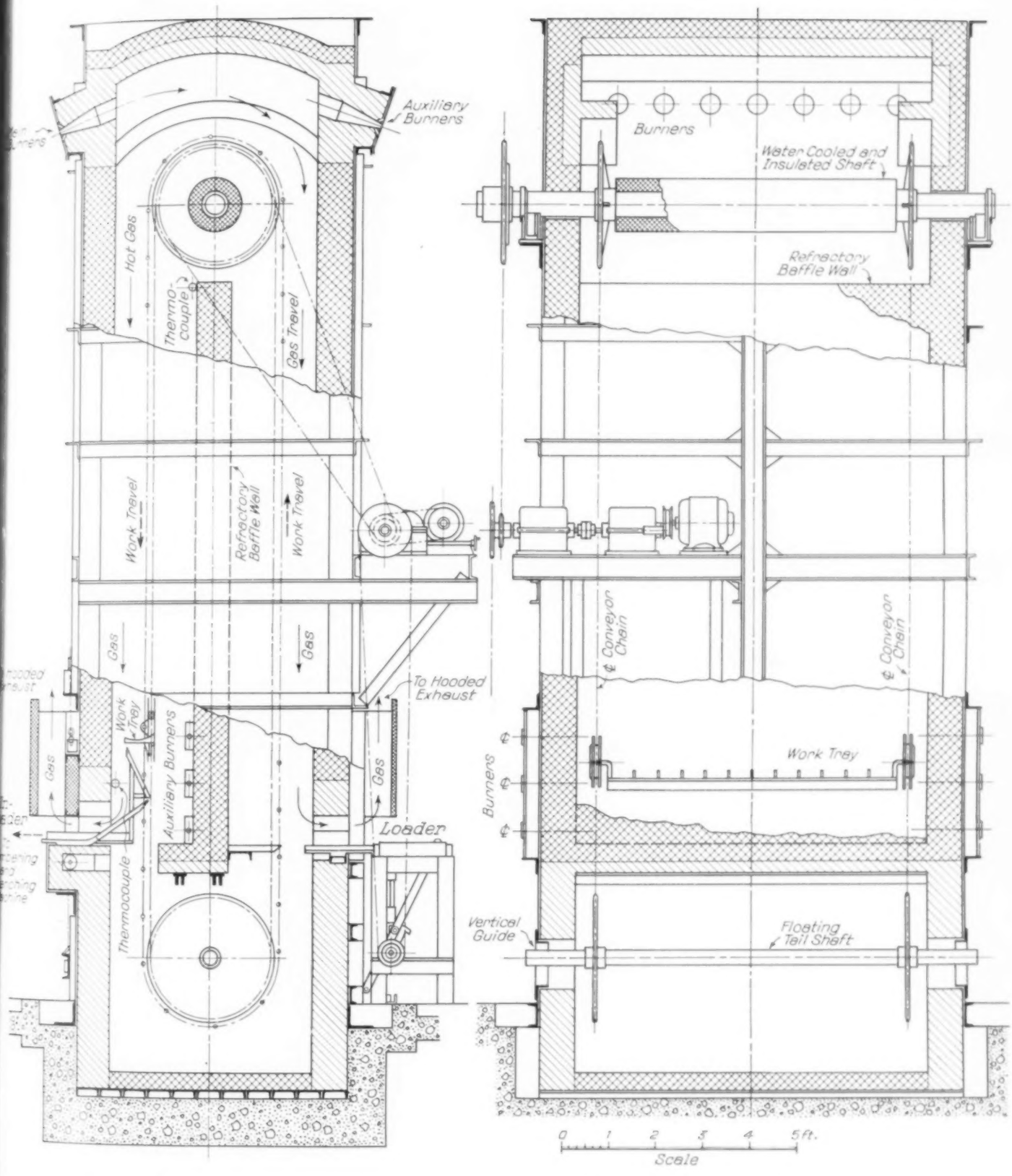
A few features of the mechanical design will be pointed out which insure proper conveyor operation, such as over-pitch and under-pitch sprockets,



Vertical Furnace for Drawing Coil Springs. All parts which are exposed to heat are of carbon steel. Single thermocouple control is sufficient, and furnace construction, vented only at bottom, insures uniform temperature on any cross-section of either ascending or descending leg

and automatic take-up at the bottom to allow for variable chain pitch as the temperature varies.

Since the head shaft carries the entire load of the conveyor assembly, fixtures and the processed material as well, additional stresses imposed by mechanical take-ups are particularly to be avoided, since temperature changes from cold to operating condition give a variable length to the conveyor.



Construction of High Temperature Furnace for Heating Spring Leaves. Thermocouple near unloader controls auxiliary burners nearby along center wall, whereas thermocouple at top of partition controls heat input of main burners. Ability of high alloys to resist loads at temperature without sagging represents limitation of this type of furnace

A "loose" chain condition is effected by the sprocket design, as shown in the sketch on page 53. For driving, the sprocket should be slightly over-pitched, while the driven or idler sprocket should be under-pitched. Otherwise, the chain may climb on the driving sprocket unless a very tight chain is maintained by the take-up. Sometimes an unbalanced load on the conveyor may cause the driven sprocket at the top to act as an idler, while the varying chain pitch due to temperature variations may put sprockets of unvarying pitch out of operation.

The sawtooth sprocket shown in the sketch on page 53 is developed for a 3-in. pitch combination chain. The extended tip and depressed root of the tooth are symmetrically balanced around the correct pitch line for the 3-in. chain, yet the chain may find its own pitch line on the sprocket and "climbing" is impossible. This type of sprocket is used both on the head shaft and the foot shaft.

As noted above, the lower sprocket rides the chain — that is, it is an idler sprocket, and the extended tooth allows a very simple take-up construction, as follows: The foot shaft carrying the lower sprockets is extended on either side through two vertical guides made of angle irons framed into the corner columns. Shaft and sprockets rest on the chain strands, and the assembly is free to move up or down with the expansion or contraction of the latter. Thus, a minimum of weight is added to the conveyor assembly, the take-up is an automatic one and the "loose" chain effect is obtained.

Crossbar attachments from extended chain pins, and fixture attachments are also indicated in the drawing on page 54. Simplicity of design and free-moving parts are incorporated throughout, to avoid conveyor trouble at the moderately elevated temperatures required for drawing or tempering operations.

This covers the essentials of design and operation for a low temperature unit. Its advantages are fairly obvious. Where vertical head room is available, the required floor space is very small for the capacities obtained. Fuel efficiencies are high, due to the low temperature of the waste gases. Forced convection with a circulating fan may be employed to increase the heating rate, although the fuel consumption is thereby increased. Continuous operation fits in well in most production lines; furthermore, practically all of the conveyor may be employed for productive work. Stock handling is most convenient, as the operator, standing in one position, loads and unloads the exposed conveyor easily.

High Temperature Furnace

For high temperature applications, say 1500° F. or above, the problem is considerably altered. Radiation from hot gases or incandescent brickwork is now the predominating factor in heat transfer instead of convection from moving products of combustion, and the thin metal baffle dividing the heating and soaking zones found in the installation for lower temperature described above is no longer adequate for proper zoning. Instead, a refractory dividing wall is required to keep the cold stock in the charging leg from cooling the stock in the discharge leg. This is clearly shown in the general drawing of the furnace printed on page 55.

Again, as the higher temperatures require a greater heat input per unit of work heated, the problem of correct heat application is considerably altered. Here each leg is controlled separately with two distinct firing points. Burners at the lower part of the discharge leg supply only enough heat for this region, while burners at the top and under separate control take care of the greater portion of the heat input required for bringing the cold stock to temperature.

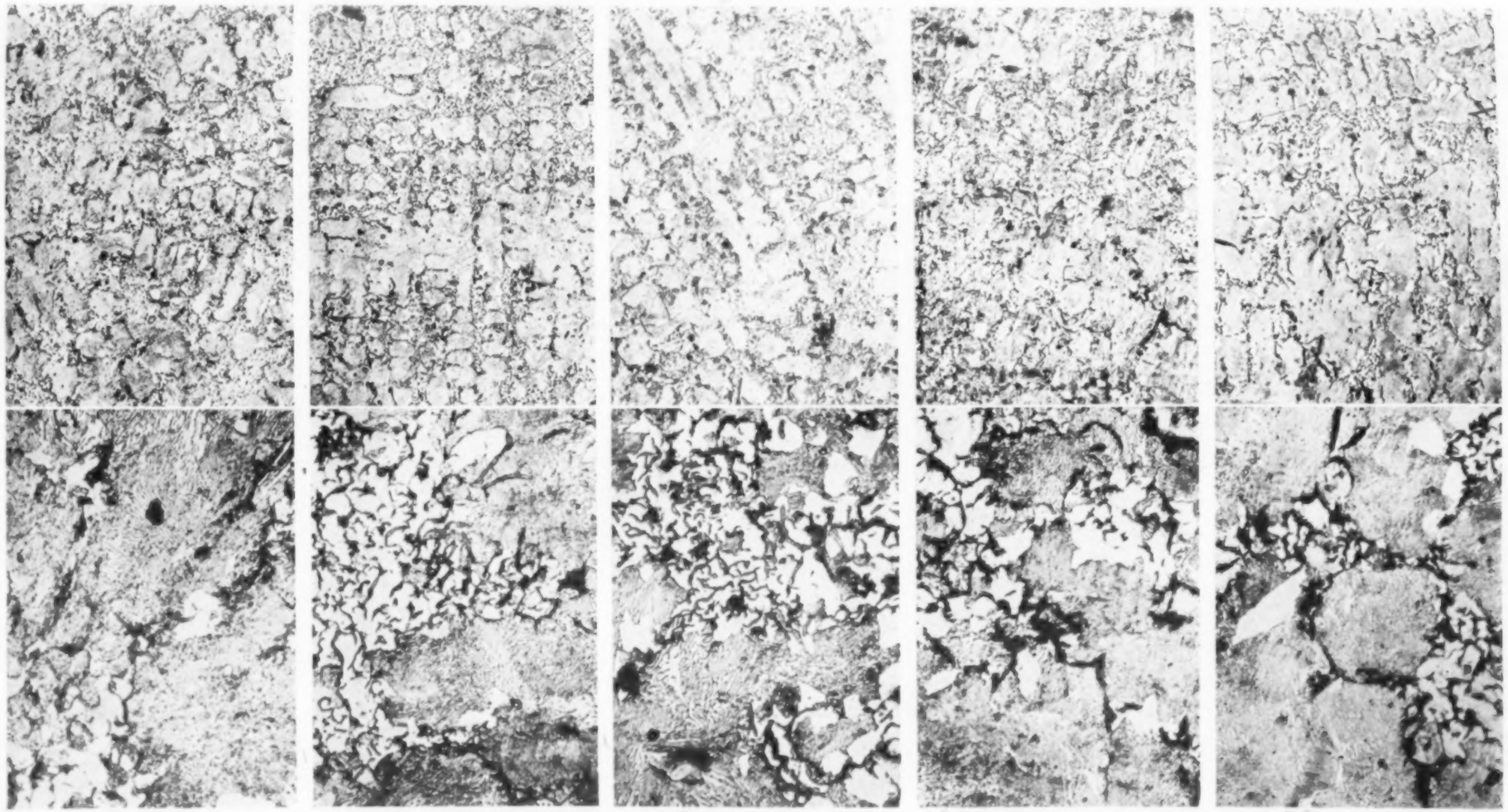
The conveyor problem also becomes much more serious as temperatures are increased. Heat resisting alloys must be employed, whereas carbon steel is amply strong for the low temperature operation. The rapid decrease in strength of materials as the temperature increases marks the real limitation of the endless conveyor belt exposed to hot gases, whether found in the vertical furnace or conventional horizontal types. Since the loads can usually be carried by rails or beams in a hearth type of furnace, whereas all the weight is carried from chains and a single shaft in the vertical furnace, the only practical application of the latter will be found in heating comparatively light sections, where the time of heating is relatively short. For the same reason, long spans between conveyor chains, with consequent sagging of shafts and work fixtures, are to be avoided in high temperature equipment.

A unit of this type has been operated successfully at Flint in the Buick plant for heating ¼-in. stock for leaf springs to a temperature of 1550° F., on a 20-min. time cycle, at the rate of 2500 lb. per hr. However, for heavier sections and heavier parts and greater capacities, this type of endless conveyor belt may not be practical. With lower temperatures and where plant conditions warrant, a vertical furnace of any reasonable width or capacity may be seriously considered.

Typical Structures of Alloy Cast Irons; Sheet 1 of 3

By M. F. Surls and F. G. Sefing, Michigan State College

Magnified 100 and 500 ×; Etched in 2% NHO3



Base Metal
Characteristic dendrites made of pearlite surrounded by fine lacy graphite associated with ferrite
3.20% C, 0.59% C.C., 0.69% Mn, 2.20 Si
36,410; 212; 2485; 0.221

1.1% Nickel
Finer "grained" dendritic structure and smaller lacy graphite particles
Combined carbon 0.67%
38,550; 220; 2350; 0.194

2.0% Nickel
Higher nickel tends to agglomerate ferrite in areas containing graphite
Combined carbon 0.78%
40,290; 240; 2570; 0.217

0.6% Molybdenum
Molybdenum tends to suppress dendritic structure, break up graphite flakes and make fine lamellar pearlite. The latter action is similar to its influence on steel
Combined carbon 0.63%
41,760; 257; 2565; 0.214

1.2% Molybdenum
Combined carbon 0.83%
49,800; 250; 2850; 0.220

The figures immediately above refer, respectively, to the Ultimate tensile strength in psi.; Brinell hardness; Tranverse strength in lb.; and Deflection in in. of the alloy iron above

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LOOPS IN WIRE-ENDS

easily stressed

beyond safety

By W. H. Swanger and G. F. Wohlgemuth
Bureau of Standards
Washington

IN 1929 a suspension bridge over Mt. Hope bay on the main road between Providence and Newport, R. I., developed trouble during construction in the form of broken wires in the main cable near their loop around the anchorage shoes. The wire was unusual in many respects and the bridge was eventually dismantled and re-erected with conventional cold drawn bridge wire (galvanized). A similar situation occurred in the Ambassador bridge over the Detroit river, constructed at the same time of the same unsatisfactory wire, and it also had to be dismantled and re-erected.

The unsatisfactory wire was made of basic open hearth steel, rolled into 4-in. square billets, reheated and rolled into 0.225-in. rods, then cold drawn one or two holes to 0.192 in., and heat treated to desired strength. Its chemical composition was the same as conventional cold drawn wire, which in existing large bridges is almost universally acid open hearth steel, cold drawn four or five holes from heat treated or "patented" $\frac{5}{16}$-in. rod to 0.192-in. wire, this cold drawing operation inducing the required strength. Both varieties are cleaned in acid and galvanized for rust protection by running through molten zinc.

Heat treatment and galvanizing of the unsatisfactory wire was done continuously by pulling the wire endwise through a series of tanks. Successive coils were butt-welded to one another and separated at the welds on emerging. Temperatures were under close pyrometeric control. The total length of the unit was 170 ft. and the wire, traveling normally, required 6 min. to make the passage. The sequence of sub-units is as follows, the wire being exposed from 2 to 4 sec. while traveling up out of one and into another.

Sequence of Treatments

Sub-Unit	*Medium*	*Temperature °F.*	*Seconds Immersion*
Preheating pan	Lead	1325 to 1350	24
First hot pan	Lead	1550	35
Hot quench	Lead	1250	33
Second hot pan	Lead	1550	37
Cleaner	Fused salts	(?)	5
Cold quench	Oil	225 to 275	90
Sand box	Sand	200 (?)	10
Tempering bath	Lead	810 to 850	18
Pickle	Dilute HCl	150	
Wash	Water	(?)	75
Flux	$ZnCl_2$ & NH_4Cl	800 (?)	
Galvanizing pan	Zinc	850	35

In the above the cleaning and galvanizing was done in conventional manner. Representative properties of the heat treated wire and the cold drawn wire which replaced it are as shown in the table at top of the next page.

	Heat Treated Wire		Acceptance Specification	Cold Drawn Wire	
	Before Heat Treatment	After Galvanizing		Before Galvanizing	After Galvanizing
Ultimate tensile strength	153,000 psi.	223,000 psi.	220,000 psi.	247,000 psi.	223,000 psi
Yield (Stress at 0.75% elongation)	—	—	190,000 psi.	—	—
Elongation in 10 in.	2%	6%	4%	3%	6%
Reduction of area	20%	38%	30%	41%	40%
Hardness, Rockwell C-scale	27	46	—	40	41

Structure of the wire in process and at the finish of heat treatment is shown in the group of three micros opposite. The question as to whether or not the final structure, which appears to be well tempered martensite, was retained permanently was investigated by thermomagnetic analysis, as described in a series of papers by R. L. Sanford and G. A. Ellinger of the National Bureau of Standards. The results show plainly that the wire was in the tempering and galvanizing baths a sufficient length of time to bring about all of the structural changes in the quenched steel that could occur at the tempering temperature, and furthermore, that no changes in the constitutional structure of the wire have since occurred.

Opinions were expressed that the use of basic instead of acid open hearth steel may have been a factor in the failure of the heat treated wire. No significant difference could be found in chemical analysis or inclusions and the use of basic open hearth steel was therefore given no further consideration as a determining factor in the failure of heat treated wire.

In addition to tensile tests it was also required as a unit of mill inspection that the wire withstand, without fracture of the zinc coating, wrapping on a mandrel four times the wire diameter.

Of the 29,221 coils of wire completely processed, approximately 4,000 were rejected in the testing room or on the processing unit. About half of these coils were rejected because of defects in the galvanizing. The remainder were rejected because of failure to meet the specified physical properties, or because they broke in the processing unit. The cause of failure to meet the specified physical properties was in most cases traced to surface defects in the rolled rod or drawn wire, such as laps, seams, overfills, and underfills that happened to be located in the test samples. The cause of most of the failures on the processing unit was not ascertained in the wire mill.

Extracts from a paper entitled "Failure of Suspension Bridge Cable Wire" read before the July meeting of American Society for Testing Materials

Fractures without reduction of area occurred in many coils shortly after they were removed from the heat treating unit; 337 such breaks were not discovered until the coils were taken from the warehouse. This condition naturally caused concern and as a precautionary measure, each coil, before it was wound on the shipping reel, was passed through two sets of staggered rolls, somewhat like a wire straightening machine. Breaks occurred in the staggered rolls in only 20 more.

Seventy-four coils were run through the heat treating unit and by-passed both acid tanks and zinc pan; no breaks occurred in any of these wires when reeled on 30 in. diameter coils.

In considering these results, hydrogen embrittlement is immediately thought of as a possible cause of the early breakages in the other coils. This is known to be a transitory effect, disappearing in time, even at room temperature. The minimum time in storage for any of this wire was 53 days, and if the wire was embrittled by hydrogen it is reasonable to expect that many more breaks would have occurred in the staggered rolls. Numerous 30-in. and 19-in. coils have been made at the U.S. Bureau of Standards from straight lengths of wire from the original cables of the Mt. Hope Bridge and subjected alternately to heat and refrigeration and various other kinds of abuse. To date, not a single break has occurred in any of them.

Although it is possible that hydrogen embrittlement may have been an important factor in causing the fractures in the coils in the wire mill, it is believed with confidence that the fractures on the Mt. Hope Bridge are not to be ascribed to it.

From these considerations and other tests to be described it was evident that the tensile properties had not been altered by preforming or by service on the bridge.

When the heat treated wire was unwound from the 7-ft. shipping reels, it would lie straight.

It was recognized that to bend this wire around the anchor shoe, 19¾ in. diameter, would stress it beyond the yield point, and since the elastic limit of the wire was so high, the wire would then be under elastic bending stresses of considerable magnitude. It was therefore decided to preform each wire at the loop around the anchor shoe, by bending it 1¼ turns around a sheave 9½ in. diameter. When released from this preforming sheave, the loop would spring open, because of the high elastic limit of the wire, to the approximate curvature of the anchor shoe. The loop was then to be placed around the shoe where it would "lie dead," and be subjected only to tensile stresses.

Construction of the bridge had progressed to the laying of the pavement when, early in Feb. 1929, a few broken wires were observed at one of the anchorages. They were scattered among a number of the anchor shoes. On Feb. 22, after a snow storm, 65 broken wires were discovered in one of the strands, and on the following day, an additional number. All of these fractures had occurred at or close to the tangent point on the anchor shoe.

The total number of wires that broke at the anchor shoes was 402, distributed as shown in the table at the top of the next column. As each wire broken at the anchor shoe left two loose ends for the wires in the cables, the breaks amounted to 804 loose ends out of the 4972 parallel wires in the two cables, approximately 16%.

The nominal static load on the cables produced a tensile stress in the wire of 32,000 psi., about one-seventh of its ultimate strength. In all of the studies made at this Bureau, the material in specimens of the fractured wires, taken close to the points of fracture, could not be distinguished, physically or chemically, from that in specimens of unfractured wires, or of fractured wires some distance removed from the point of failure. The logical conclusion is that the stress conditions at the anchor shoes were radically different from those in the compacted cables.

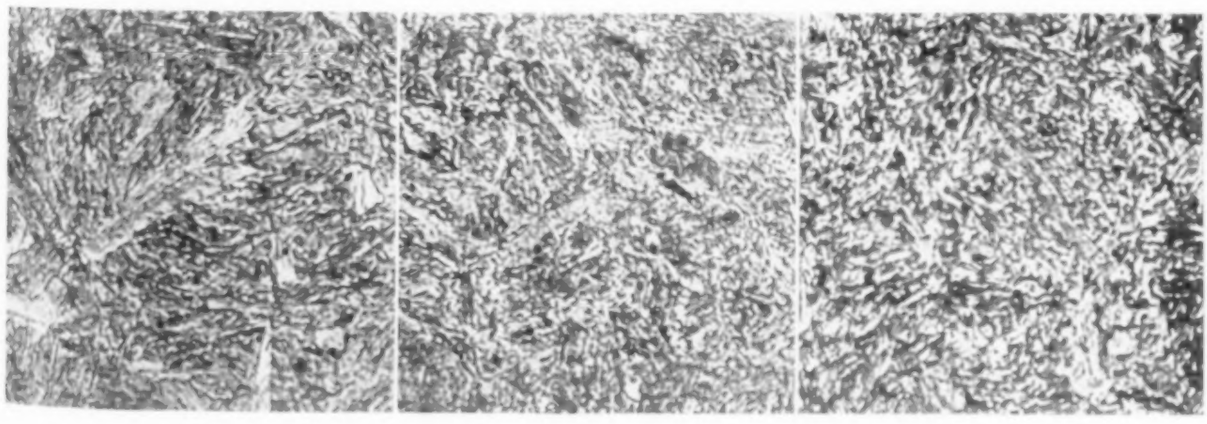
Number Broken Wires in Each Strand

Strand No.	East Cable			West Cable		
	Anchorage Bristol	Anchorage Portsmouth	Total	Anchorage Bristol	Anchorage Portsmouth	Total
1	140	4	144	4	6	10
2	6	10	16	3	2	5
3	7	16	23	10	129	139
4	4	11	15	3	0	3
5	2	3	5	1	1	2
6	2	22	24	6	1	7
7	2	2	4	3	2	5
			231			171

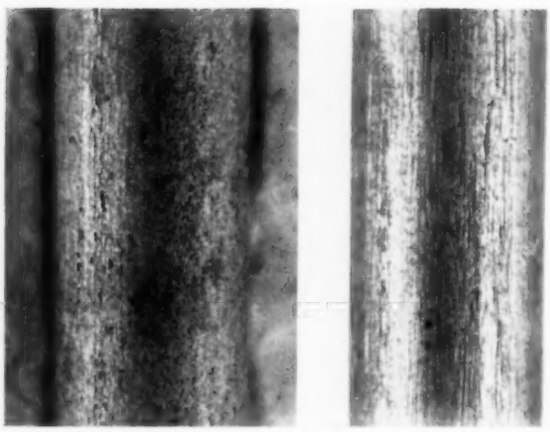
The fact that 67% of the breaks were concentrated at two of the 28 anchor shoes cannot be attributed to the chance location at these points of wire from one or more bad heats of steel. Wire from 21 heats was present in both strands. No systematic differences were observed in the anchor shoes themselves and the equal load distribution wire to wire was not questioned.

In adjusting the sag for each completed strand, the anchor shoes at each end were moved backward or forward and held by shims. It is possible that at the two anchor shoes in question, the tensile load on the strand differed from the loads at the other strand shoes.

Several hundred tension tests made at the Bureau showed good agreement in all cases with specified requirements with the exception of some low values for reduction of area (also experienced in the original inspection). In any



Microstructure of Heat Treated Wire. All at 2000 ×. At left, air cooled from middle of tempering bath; center, air cooled after quench; right, finished wire



Appearance of Surface of Wire From Mt. Hope Bridge After Stripping Zinc Coating; Left is Heat Treated Wire; Right is Cold Drawn Wire. Magnified 6 times

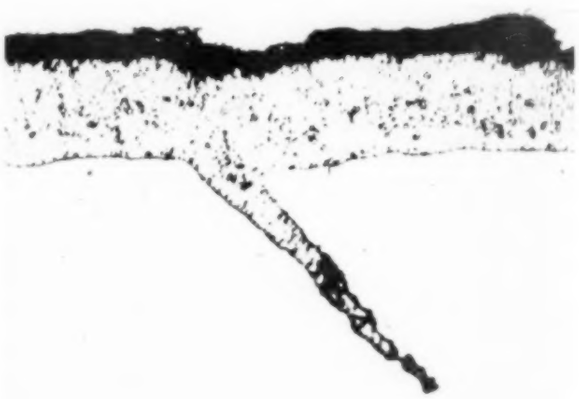
length of wire, either from the loop around the anchor shoe or from a straight portion, it was found that, generally, one out of seven to ten tensile test specimens fractured with practically no reduction of area. Very seldom did adjacent specimens from the same piece have abnormally low reduction of area, hence such wire was accepted by the inspectors on a retest at the production plant.

It was found that the cause of deficient ductility lay in the surface conditions of the wire. When the outer layers of the galvanized wire were removed mechanically to a depth of 0.015 in., all low reduction breaks were eliminated. It is noteworthy also that removal of the galvanized coating and the shallower surface defects did not cause any marked improvement. The decrease in ductility was evidently caused by the more deeply seated defects, occurring sporadically, but apparently in all of the wire.

The pitted appearance of the heat treated wire as well as the cold drawn wire which replaced it, after stripping the zinc is shown at 6 diameters magnification in the adjoining half tone. Deep seated defects in longitudinal section appear at frequent intervals in the heat treated wire; these are shown at 100 diameters.

An early suggestion was that the essential cause of the fracture might be a slowly creeping tensile load on a wire bent to such a curve that its extreme fiber was stressed beyond the yield point. To try out this hypothesis, specimens of wire about 8 ft. long were subjected to static tensile loads while looped over a support that had the curvature of the anchor shoes. Five of these units were used. Some of the specimens were not preformed, others were; some were hairpins from the bridge. The initial tensile load was 90,000 psi., and it was increased by 10,000 psi. increments at definite time intervals.

Of the 135 specimens of the heat treated galvanized wire, only eight broke at tensile stresses less than the nominal ultimate tensile strength, and none at a tensile stress less than 120,000 psi. Apparently the elastic bending stresses had not much effect in lowering the effective resistance of the specimens to static tensile loads. It is possibly significant that the low fractures in the eight specimens all occurred in the portion in contact with the support. Thirty-four of this group broke with less than 20% re-



Relatively Deep Cracks, Filled With Zinc or Zinc-Iron Compound, Occurred Frequently in the Heat Treated Wire. Longitudinal section, magnified 100 ×

duction of area at the point of fracture. The bending stresses acting in conjunction with the tensile stresses evidently did tend to cause a higher than normal proportion of the brittle type of fracture. However, the results of the static loading under combined stresses cannot be accepted as an explanation of the mechanism of failure of the wire on the bridge.

Next attention was devoted to the endurance under alternating loads. Results of extensive fatigue tests of the failed wire and of the cold drawn type of bridge wire have already been published in *Proceedings*, A.S.T.M., 1931 and 1933. Tests were made by the rotating beam method on both varieties of wire—*(a)* in the galvanized condition, *(b)* after the galvanizing had been stripped, *(c)* then polished and *(d)* machined to 0.150 in. A similar program was carried out in a Haigh machine where direct tension loads at various ranges were applied. The results are summarized in diagrams alongside, wherein it is notable that the unsatisfactory heat treated and

the satisfactory cold drawn wires acted in substantially the same manner.

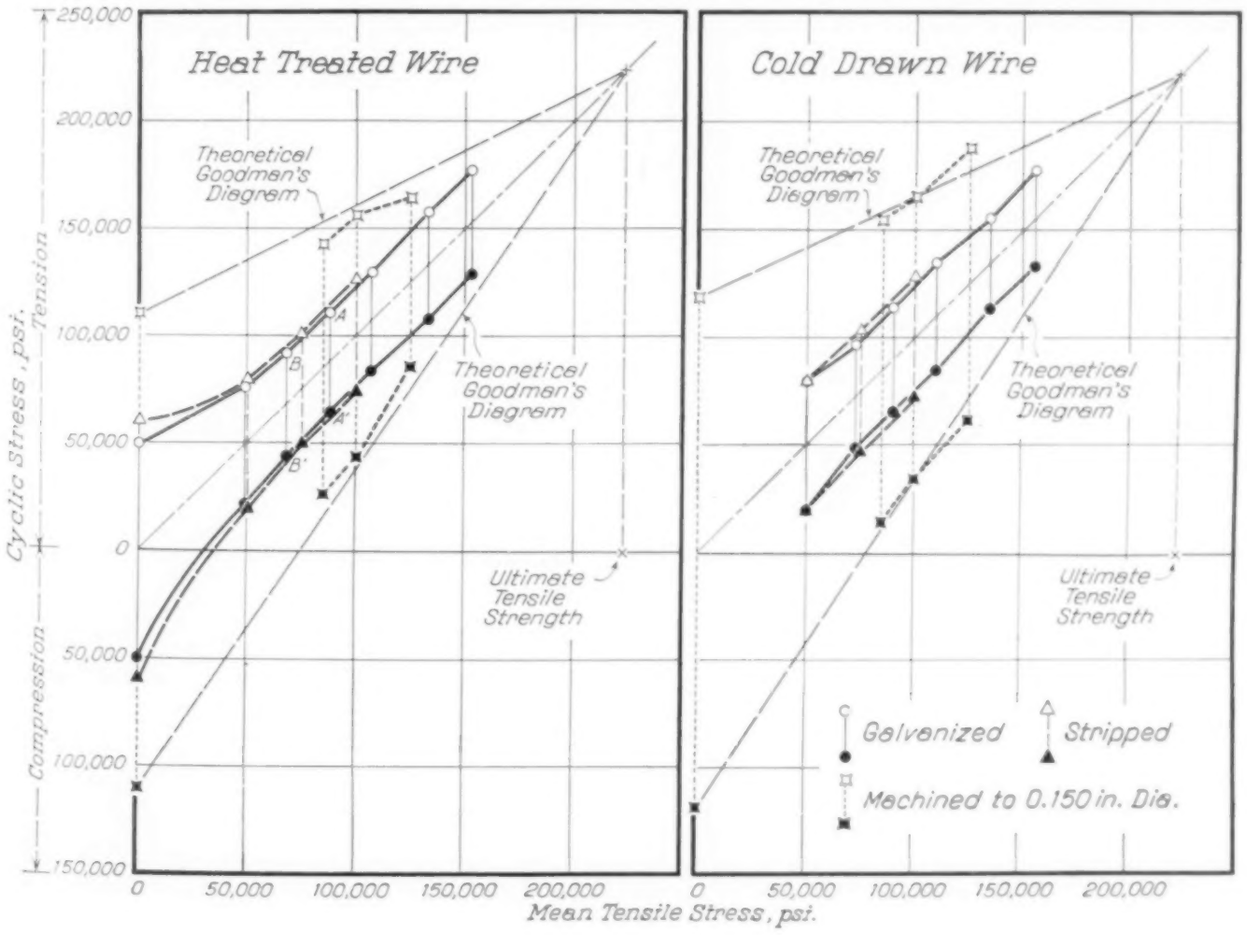
It had been ascertained that in the heat treated wire the fractures that occurred at stresses below the nominal tensile strength, including those at the anchor shoes on the bridge, invariably originated at the surface. It was evident from fatigue tests on galvanized or stripped samples that conditions at the surface of both varieties of wire were causing a drastic reduction in the resistance to repeated stresses. Except for the decrease in the amount of reduction of area at the point of fracture in a tensile test, such defects even when rather deep did not, in general, affect the other tensile properties.

In the case of the failed wire, the minor surface pits were undoubtedly formed where the effects of mill scale or other rolling defects had not been ironed out in the one or two drafts the wire received in drawing. The cold drawn wire, drawn through five dies from hot rolled rod, had a much smoother surface with few pits.

The wires in suspension bridge cables are tension members, and stresses that cause fatigue fractures can arise only from fluctuations in *tensile* load. The Haigh machine produces this type of loading, and the diagram shows that even though the ultimate tensile strength of each type of wire was 223,000 psi., the maximum range of pulsating tensile stress, at mean stresses from 50,000 to 150,000 psi. was only approximately 50,000 psi. for the galvanized wires — less than one-quarter of their ultimate strengths. Moreover, the heat treated wire, with a much more severely pitted surface on the steel than the cold drawn wire, yet had an endurance strength, both with and without the zinc coating, approximately as great as that of the cold drawn wire.

Of the many specimens of both types of wire broken in the fatigue tests, only one of each type was obtained in which the nucleus of the fatigue fracture was in the interior of the section. Both were machined specimens. This fact is one item of evidence that internal cracks or fissures in

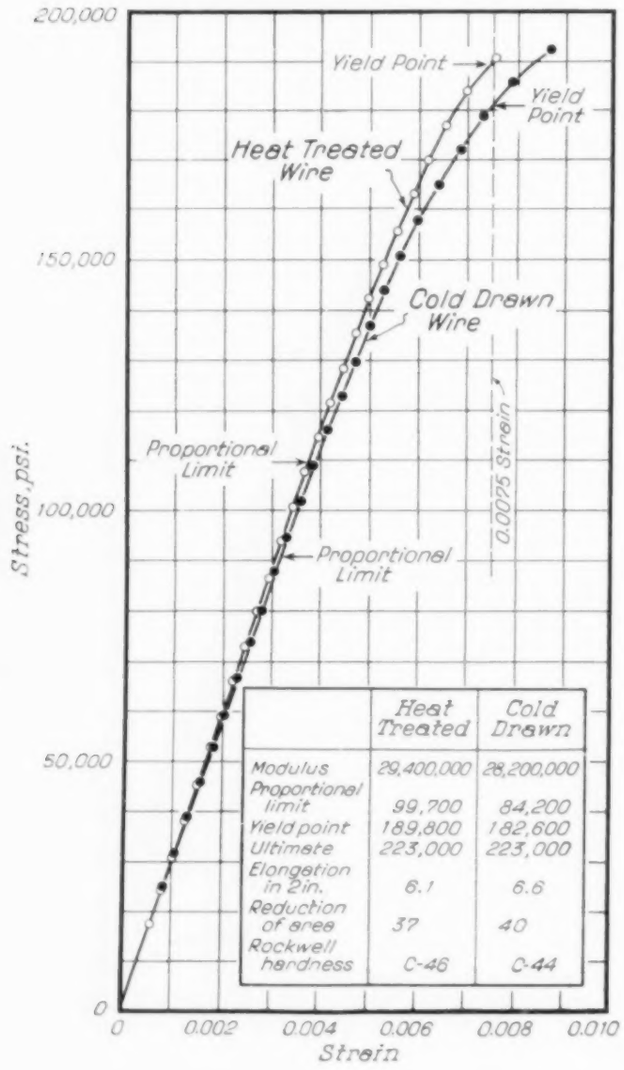
Summary of Fatigue Tests on Bridge Wire. Points plotted at zero ordinate were secured in rotating beam style of test. Other points, such as A, A', were secured in a Haigh machine, where direct tension can be imposed and varied systematically. Lines marked "Theoretical Goodman's Diagram" were added by the Editor, and represent the expected safe stress range for material with unblemished surface



the heat treated wire, or an undue number of inclusions, or incorrect melting practice were not a cause of its failure on the bridge.

These results prove that if the heat treated wire failed by fatigue at the anchor shoes on the bridge, it did not occur because its strength was less than that of the cold drawn wire which replaced it, for the latter was subjected to the same loading conditions during the reconstruction of the bridge. It does not follow, necessarily, that under the same loading conditions at the anchorages, the *stress* conditions in the portions looped around the anchor shoes were the same in the two types of wire.

Stress-Strain Curves of Two Varieties of Bridge Wire of Equal Ultimate Strength. Average of ten determinations. Note lower proportional limit and modulus of cold drawn wire



It was apparent, therefore, that a knowledge of the stress conditions in the wire at the points where the fractures occurred would be most useful to the investigation of failed loops at anchorages.

A total of 1181 hairpins from the bridge were traced on a lay-out floor, and the deviation between the curvature of the "strain free" or unloaded wire and its curvature when snugged close to the anchor shoe was determined. Not a single wire, of all those examined, was curved to fit accurately the curvature of the anchor shoe. Many had reverse curves; others contained rather sharp bends or kinks. In practically all of the wires, the point which had coincided with the midpoint of the circular curve on the anchor shoe was not at the midpoint of the curved portion of the wire. The preforming operation had failed completely in accomplishing its purpose of shaping the wire to fit the anchor shoe; indeed, in many cases the wire had been *deformed* so that, when snugged close to the shoe, bending stresses were induced that were greater than if no attempt had been made to shape the wire to fit its end bearing.

The cold drawn wire in the "hairpins" used to repair the broken wire on the bridge was curved regularly and uniformly on a 40 in. radius when released from lateral constraint. It is easily calculated that bending deflections in many of the heat treated wires, when they were forced to the shape of the anchor shoes by a tensile pull on the wire, were greater than the bending deflections imparted to the cold drawn wires in the same manner.

Cold Drawn Wire Deforms Plastically

A study of the stress-strain relations in tensile tests of straight specimens of both types of wire, is summarized in the adjoining diagram. It discloses that for equal deflections (strain), the stresses were greater in the heat treated than in the cold drawn wire. In these tests the specimens were loaded progressively, each increment of load being held only for a sufficient time to read the extensometer. The proportional limits were determined by the method proposed by L. B. Tuckerman using a deviation of 0.00002 in. per in. as a criterion. The modulus of elasticity of each specimen was computed as the average slope of stress-strain curve as far out as the proportional limit.

Determinations were also made of the permanent set after release of tensile stresses maintained for 1-hr. and 48-hr. periods. A new specimen was used for each determination. The tabular results on the next page show that in the heat treated wire there were no significant differences between the permanent extensions after 1 hr. and 48 hr. until 184,000 psi. was reached. In the cold drawn wire the permanent extensions after 48 hr. at the stresses of 150,000 psi. and higher were appreciably greater than those produced in 1 hr. Of more significance

is the fact that the permanent extensions for a given stress in the cold drawn wire were greater than those in the heat treated wire, and that creep occurred in the cold drawn wire at stresses below the yield strength (182,000 psi., the stress for 0.75% strain).

These results were checked qualitatively by observing the spring back of straight wires pulled down over anchor shoes with given tensile stresses held for varying time.

Permanent Set in 8 in. After Stay Under Tensile Stress

Stress	One Hour Stay		48 Hours Stay	
	Heat Treated	Cold Drawn	Heat Treated	Cold Drawn
33,000 psi.	0.1%	0.5%	0.1%	0.1%
67,000	0.3	0.8	0.3	0.8
83,000	0.2	2.2	0.4	1.0
100,000	0.4	2.6	1.3	1.8
117,000	1.1	4.0	1.2	4.9
133,000	2.1	5.6	1.6	6.1
150,000	3.6	9.0	3.0	11.9
167,000	9.0	18.6	7.3	25.5
184,000	21.1	48.0	31.0	67.9

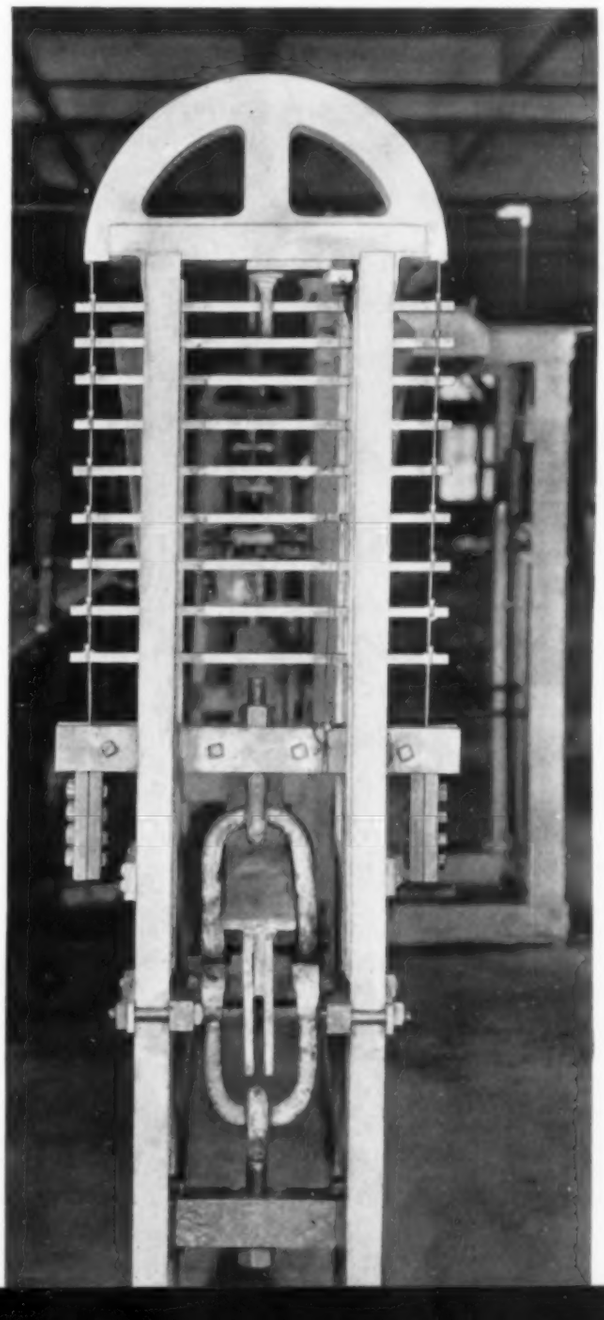
All these results were in accordance with the conclusion that elastic bending stresses existed in the loops of the heat treated wires around the anchor shoes which were greater than those in the corresponding portions of the cold drawn wires when the cables were replaced.

However, if these elastic bending stresses resulted from *constant* tensile loads, or from *continuously increased* tensile loads, applied by the pull of the cables on the anchor shoes, they were not sufficiently greater in the heat treated wire to account for its failure on the same bridge where the cold drawn wire has proved to be adequate. When the tensile stresses resulting from the progressively increased tensile loads became equal to the elastic limit, plastic extension took place, causing a decrease in the elastic bending stresses, and the tensile stresses then became the predominating factor. If, however, the tensile load on the wires fluctuated from its maximum value, at any instant, to a lower value, the elastic bending stresses in the wires would also fluctuate over a range, provided that the decrease in tensile load permitted a change in the curvature of the wires.

Only circumstantial evidence is available to show that during construction of the bridge the tensile pull did fluctuate. Such fluctuations come especially from wind forces occurring during the spinning operation. (Visible oscillations of the cables were noted by observers from the National Bureau of Standards at the time the bridge was dismantled.)

It was evident that the maximum change in elastic bending stress would occur when there was a decrease in the tensile pull from a maximum value which was just sufficient to hold the wire closely to the contour of the anchor shoe. Such conditions undoubtedly occurred during the spinning of the cables.

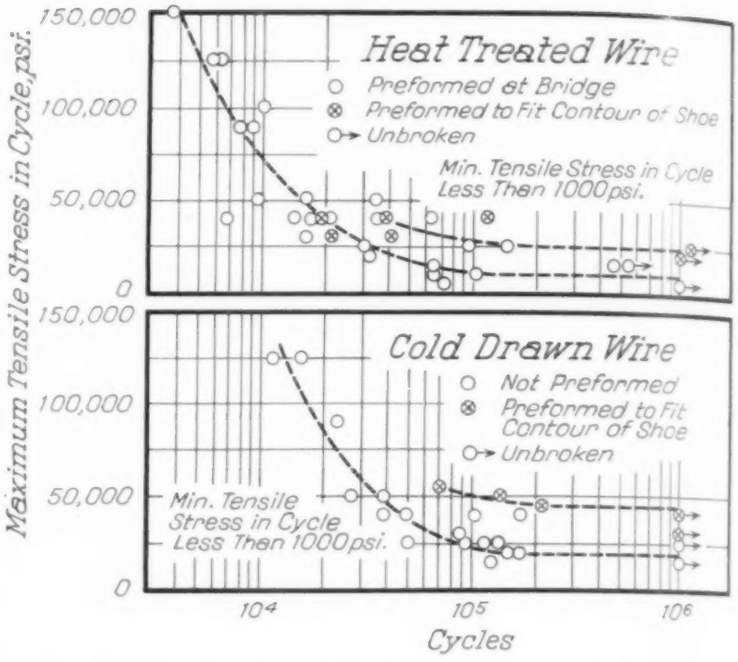
Such fluctuating tensile loads were obtained in the laboratory by alternately removing and replacing suitable counter weights at the end of



End View of Testing Fixture Simulating Conditions at Anchor Shoe. Load may be applied in a static, increasing or fluctuating manner by control of weights at the rear end of a lever system. When the straight portions of the wire are held straight, as with the nine cross yokes shown, they develop normal endurance limits, but when periodic relief of load causes slight changes in the curvature at or near the loop (no yokes present) failure occurs at abnormally low values

the lever arm of the testing fixtures designed to test a loop of wire by static and creeping loads. The specimens were looped over the semi-circular support on top of the frame, and the load at the rear end of the loading lever raised and lowered by a motor-driven cam.

This program of tests is summarized in the S-N diagram. For the same conditions of curvature of the specimen and ranges of tensile load, no differences in results were observed between wire recovered from the bridge and the new wire. The galvanized coating was present on all specimens. A tensile stress of approximately 50,000 psi. was required to pull the specimens of both types of wire into position over the support so that a further increase in tensile stress caused no apparent change in curvature of the specimen. In the range 0 to 50,000 psi. small changes in tensile stress caused visible changes in curvature of the specimens. The greatest change in curvature occurred when the tensile stress was changed from 50,000 psi. or higher to the minimum obtainable in the apparatus.



Stress-Cycle Diagram Showing Early Failure in Loops of Wire Under Fluctuating Loads When Tested in the Fixture Shown on Page 65

In general, at equal ranges of tensile stress, the cold drawn wire endured a distinctly greater number of cycles before fracture than did the heat treated wire. Although there is considerable scattering of the plotted points from a smooth curve, the S-N curves show the increase in number of cycles as the maximum tensile stress of the range was decreased, with a definite trend to a constant range within which fractures were not obtained in one million cycles. For the heat treated wire, this range was only from 600 to 10,000 psi., a rather startling fact for wire with an ultimate tensile strength of 223,000 psi. and mounted as a tensile member in the same manner as it was installed on the bridge. This paradox is due to the fact that fractures were directly the result of the range of bending stress incurred when the tensile loads were alternately increased and decreased.

In all of the specimens of both types of wire, the fractures occurred without any deformation at the point of fracture. The surfaces of fracture had the distinctive characteristics of fatigue fractures with the point of origin at the surface of the wire. The appearance of the fractures in the heat treated wire has a striking similarity to those that occurred on the bridge, also shown in the photographs on page 67. Many broken ends of wires recovered from the bridge were sectioned longitudinally, through the surface of fracture. A very few were found to contain deep pits filled with zinc at the apparent point of origin of the fracture, and they undoubtedly hastened the progress of the fracture.

When the heat treated wire specimens were preformed to fit the support, so that very little bending took place as the tensile loads were increased and decreased, the range of tensile stress to permit one million cycles without fracture was increased 2.5 times, as shown by the upper curves in the graph. Even under these circumstances, the range, 600 to 25,000 psi. was less than the safe range of pulsating tensile stress under purely axial loading conditions (Haigh machine). This indicates that it was impracticable to preform this wire at the bridge so as to avoid damaging bending stresses in the loops at the anchor shoes when the tensile loads fluctuated.

For the cold drawn wire, not preformed, the range of tensile stress, when the minimum was less than 1000 psi., was also surprisingly low. When this wire was *carefully* preformed it was possible to raise the maximum tensile stress to 45,000 psi. without causing fractures in one million cycles. This range was almost as large as the safe range of pulsating tensile stress obtained in the Haigh machines on straight specimens.

As it was evident that the tensile stresses alone could not have caused the fractures, but that they were a direct result of bending stresses, observations were made of the behavior of specimens subjected to fluctuating tensile stresses but so constrained that the changes in curvature were as small as possible. By means of rigid braces fastened to both limbs of the U-shaped specimens practically no bending of the specimen occurred when the tensile loads fluctuated. Instead of breaking in from 500,000 to 1,000,000 cycles of tensile stress ranging from 600 to 10,000 psi. it was possible to raise the maximum stress of the cycle to 40,000 psi. without causing fractures in 500,000 cycles.

In summary, the results of the fluctuating tensile load tests showed that it was entirely possible to produce fractures in the bridge wire as the result of fluctuations in tensile load, when the tensile stress at no time exceeded the maximum calculated for the wire in the cables of the Mt. Hope bridge at the time it was dismantled, and the fractures on the bridge were the result of the same *kind* of stresses as those that caused the fractures in the fluctuating tensile load tests in the laboratory.

DISCUSSION

By Ernest E. Thum

Editor, METAL PROGRESS

MANY FACTS about the performance of the heat treated bridge wire during manufacture are contained in the comprehensive paper by Messrs. Swanger and Wohlgemuth, which have hitherto been held confidential. Consequently it is an essential document in the history of suspension bridges and bridge wire. The above abstract, necessarily brief, omits most of the data already well known and published previously in a literature now grown rather extensive.

Numerous hypotheses have been advanced as to the reason why heat treated wire failed in service whereas cold drawn wire has been uniformly successful for suspension bridge cables, even though the former passed the usual acceptance tests. The principal ones were examined by the Editor of **Metal Progress** in four articles starting in June, 1932. Failure was not due to abuse during erection nor abuse during manufacture. It was not due to the use of steel unsuitable in analysis or melting practice. Furthermore the constitution of the heat treated steel was stable and has not changed since the wire was

(Continued on page 82)

Fractures from Mt. Hope Bridge, Magnified 6 ×

Fractures Produced at Bureau of Standards

QUALITY TOOL STEEL

is tested for hardenability

By Reinhold Schempp
Metallurgist
Halcomb Steel Co.
Syracuse, N. Y.

THE CONSEQUENCES of selecting and using an unsuitable type of steel for a given application are well known. In general, the grade of steel to be used for a certain part or tool is determined by experience — that is, either by trials under actual service conditions or by analogy with the performance of other parts and tools operating under conditions similar to the particular job under consideration.

This method of selecting alloy steels, especially those which are most commonly used in the automotive industry, has resulted in a multitude of specifications based principally upon chemical composition and physical properties. In the case of tool steels, however, the problem of defining one's quality requirements in a more or less clear-cut specification is considerably more difficult because of the lack of a standard yardstick which would allow us to evaluate certain of the essential properties and characteristics of this class of steel.

Aside from the approximate chemistry of the tool steel, its hardness, and (possibly) the structure in the as-received condition, the consumer is buying "tool steel making ability" today, as he always has in the past.

This "tool steel making ability" which permits the steel mills to manufacture a product whose response to heat treatment and whose service performance is consistent and uniform, represents a combination of experience, technical knowledge and continued scientific research, and may well be termed the function of tool steel "quality." While experience has unquestionably been the basic teacher in the development of steel making practices, it is the technical understanding, together with the unceasing search for the yet unknown, which is now responsible for quality control in tool steels.

In the following a brief description is presented of some of the most frequently discussed features of quality control, that is, hardenability and hardening characteristics of straight carbon tool steels.

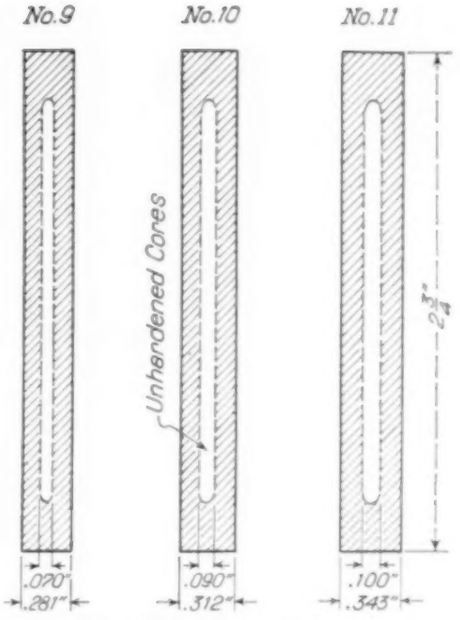
Hardenability, as the name implies, is the steel's ability to respond consistently to a heat treatment in such a manner as to produce a certain depth of hardened (martensitic) case. It must be recognized that this term may only be used when size and section (mass), prior structural conditions, heating time and temperature, as well as the quenching medium, are known and held quite constant.

Since the depth of hardening is solely dependent upon the "critical rate of cooling" from hardening temperature, hardenability control must necessarily cover all the factors which may influence this cooling rate or speed. The me-

chanical features of the hardening technique, that is, size and section, time at temperature and nature of cooling medium, are rather simple to control and it should be obvious that it is the structural condition of the specimen at the time of quenching which is the real factor controlling the steel's hardenability.

When speaking of the hardening characteristics of tool steels, we refer to the inherent properties of individual melts which govern the steel's response to heat treatment in general. This response is not necessarily confined to the case depth and grain refinement, which may be obtained in the quenching from various temperatures, but includes the steel's response to such treatments as normalizing and annealing.

It is readily seen, then, that while the hardenability of tool steels cannot be considered an absolute constant, it is truly an inherent characteristic and must be held consistently and uniformly within certain limits if we are to speak of quality control of our melts.



Disks of High Carbon Tool Steel Are Hardened Under Definite Conditions; Hardenability Number Is Proportional to Thickness of Fully Hardened Disk

Tests for Quality Control

In order to insure uniformity and consistent service performance, it has been essential for the maker of quality tool steel not only to depend on his ability to control the melt, but also to devise testing procedures which would allow a routine check on the inherent characteristics of each individual heat and its classification, and, subsequently, an intelligent application of the product. The following will give a brief description of some of the tests to which, aside from chemical analysis, every melt of high carbon tool steel material is being subjected by the Halcomb Steel Co.

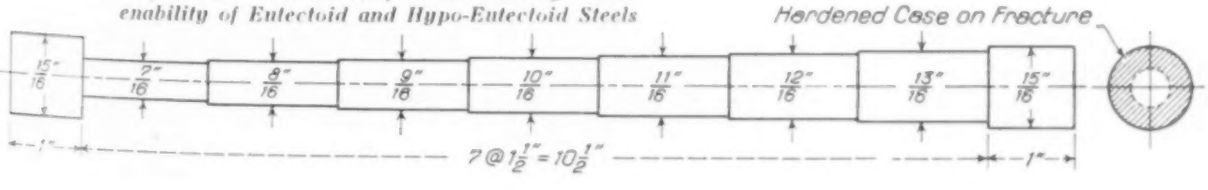
Classification According to Inherent Characteristics — To determine the inherent hardening characteristics of a heat, representative test specimens from full size ingots are hot worked, and subsequently machined to ¾-in. round by 3-in. long pieces, five of these pieces being prepared for each heat of hyper-eutectoid carbon steel and four for heats of eutectoid or hypo-eutectoid composition. After a precautional 1600° F. oil treatment, one specimen is hardened by brine quenching from each of the following temperatures: 1450° F., 1500° F., 1550° F., 1600° F. After hardening, each piece is fractured in the center, one-half of these pieces are ground flat and etched in 1:1 hydrochloric acid to show clearly the depth of hardening, and the other half is visually examined for its fracture grain condition. The case depth (martensitic area) is measured in 64ths of an inch. The texture of the fracture (case) is rated by comparison with Shepherd's Fracture Grain Size Specimens, ranging in numbers from No. 1, open and coarse to No. 10, fine and silky. For instance, if this test shows that the ¾-in. specimens hardened from 1450°, 1500°, 1550° and 1600° F., have hardened case depths of 7/64, 8/64, 10/64 and 12/64 in. respectively, and a fracture grain condition rated as 9, 9, 8½, 8, the heat classification would be noted as follows:

7, 8, 10, 12 — 9, 9, 8½, 8.

The fifth specimen which, as before stated, is prepared only on hyper-eutectoid melts, is given a 1450° F. anneal (subsequent to the 1600° F. oil treatment) and hardened by brine quenching from 1450° F. The hardened case depth and the fracture grain appearance are then measured and observed as noted above.

Hardenability — The response of the heat to a definite hardening treatment (that is, its hardenability) is determined *(a)* on hyper-eutectoid

Step Down Test Piece for Determining Hardenability of Eutectoid and Hypo-Eutectoid Steels



steels by the well known slab test. Duplicate sets of 2¾-in. round disks are machined and accurately ground to three definite thicknesses, the required thickness being a function of the melting practice employed in making the material under test. That is, if the desired stock was one which when quenched from 1420° F. will just harden through a 9/32-in. section, the thicknesses of the small slabs machined would be 9/32, 10/32, and 11/32.

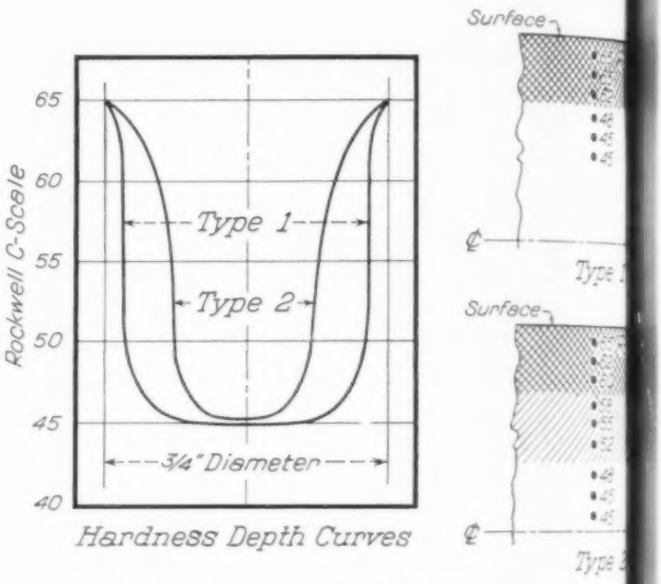
After the oil quenching from 1600° F., which is used to eliminate any variation or possible influence of prior structural conditions, one set of disks is hardened from 1420° F. and the other from 1440° F. in brine, using a special quenching fixture. The hardened disks are cut in half by a friction wheel, the cross section of one piece then being polished and etched in 1:1 hydrochloric acid to give a sharp demarcation case and core. The hardenability rating is the numerator of the fraction in 32nds measuring the thickness of the thinnest disk which shows a definite soft core. In other words, if the 9/32 disks have hardened through and the 10/32 disks show a slight core, the material would be rated as having No. 10 hardenability. This is the Shepherd hardenability rating; it has been well described by the sponsor in METAL PROGRESS, Feb., 1931, page 51.

(b) On eutectoid compositions hardenability is judged by a so-called stepdown test which is carried out in the following manner. Representative test pieces are made into 1-in. round x 12-in. long specimens and annealed at 1450° F. These pieces are then machined in 1½-in. steps ranging in size from 14/16 in. to 7/16 in. diameter, in increments of 1/16. (See sketch on page 69.) After a 1600° F. oil quench, these test specimens are brine quenched from 1475° F. in a vertical jig. Each step is then centrally cross sectioned, polished, etched and examined for hardness penetration. The hardenability rating is evaluated by using the numerator of the section diameter in 16ths which shows the first indication of a definite core. (The reason for rating the slab-hardenability test results in 32nds of an inch and the stepdown hardenability test results in 16ths is that the slab test is more sensitive to slight variations in the steel on account of the rather thin sections which are being hardened.)

After choosing suitable steel for specific orders, careful cleaning of billets, finish rolling or forging under pyrometrically controlled heat, the finished and annealed bar stock is checked by the following inspection methods:

1. Block test for the annealed fracture inspection.
2. Bench inspection for surface condition and size.
3. 100% disk inspection for hardness, macro etch, hardened fracture and decarburization.

Judicious interpretation and correlation of the results obtained by these various tests permit the commercial manufacture of tool steels having superior quality characteristics, capable of meeting the consumers' ever-increasing demands for higher production and more severe service.



Type 2 Grades More Gradually in Hardness From Surface Inward than Type 1; Higher Quenching Temperatures Drive Hardness Deeper Without Coarsening the Fracture

As an example, take the mill's typical classification of heats of straight 1.00 to 1.10% carbon tool steel. Based on the inherent characteristics of the melt, these are definitely differentiated among four types.

Type 1: Melts of this type are inherently rather shallow hardening. With increasing quenching temperature they show practically no increase in the martensitic case depth of the ¾ in. round specimen and their fracture grain refinement is fairly fine, regardless of quenching temperature.

Type 2: With an increase in the hardening temperature, material of this type will show some increase in case depth, which is accompanied with but little or no coarsening of the fracture grain appearance.

Type 3: This type with increasing quenching temperature will show little if any increase in case depth, but *(Continued on page 72)*

THIS is vacation time. Millions of people are away. Other millions are getting ready for trips—to mountains and seashore and lakes—to the country or to foreign lands.

Distance doesn't matter any more. Your family may be scattered temporarily to the four winds—children at camp, mother visiting back home, father at the office—but all may be reunited again, instantly, by the simple calling of a number.

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considerable coarsening of the fracture grain size.

Type 4: With increasing quenching temperature, melts of this type will show a material increase in both martensitic case depth and fracture grain size.

Although material of Types 1 and 4 have a definite place for certain applications, while Type 3 material is naturally undesirable, Type 2 has rightfully earned for itself the name "general utility type." With it the user can obtain the desired depth of hardening on any reasonable size of part by simply adjusting the quenching temperature — that is, small sizes and sections are preferably quenched from the normal hardening temperature of approximately 1450° F., while tools of larger cross section and mass may be successfully quenched from higher temperatures, up to about 1600° F.

The reason for this deepening of the case, with quenching temperature, in Type 2 material may possibly be a substantial transition zone between the case and core. Material of Type 1 shows a very sharp line of demarcation between case and core and a quick hardness drop from approximately C-65 to C-62 to about C-48 to C-45; while in Type 2 a transition zone exists between the case and core with gradually diminishing hardness. This is shown in the accompanying diagram on page 70. Consequently, any increase in hardening temperature will result in a sufficient additional suppression of the austenite-pearlite transformation as to permit part of the before mentioned transition zone in Type 2 to become fully martensitic — in other words, add itself to the hardened case.

Another rather interesting feature about prior structure is probably well known to many practical heat treaters and metallurgists, yet has not been discussed a great deal in literature: With constant quenching temperature and similar hardening conditions (the quenching temperature however, not being higher than approximately 50 to 75° above Ac_1) hyper-eutectoid carbon tool steels will harden deeper when treated from a prior spheroidized structure than when quenched from a sorbitic or partially lamellar pearlitic structure.

An explanation for this phenomenon, which is readily recognized as a matter of carbide solution, was attempted by determining the effect of the structural condition upon the excess amount of carbide present in hyper-eutectoid steels (1.06% carbon). By dissolving representative samples of different structural conditions in cold nitric acid (38% HNO_3) the following results were obtained: 0.35% of carbon was difficultly soluble in a sample with completely spheroidized structure (Rockwell B-83); corresponding results were 0.14% for sorbitic structure containing many tiny particles of carbide (Rockwell C-39) and 0.16% for 70% lamellar pearlite (C-32).

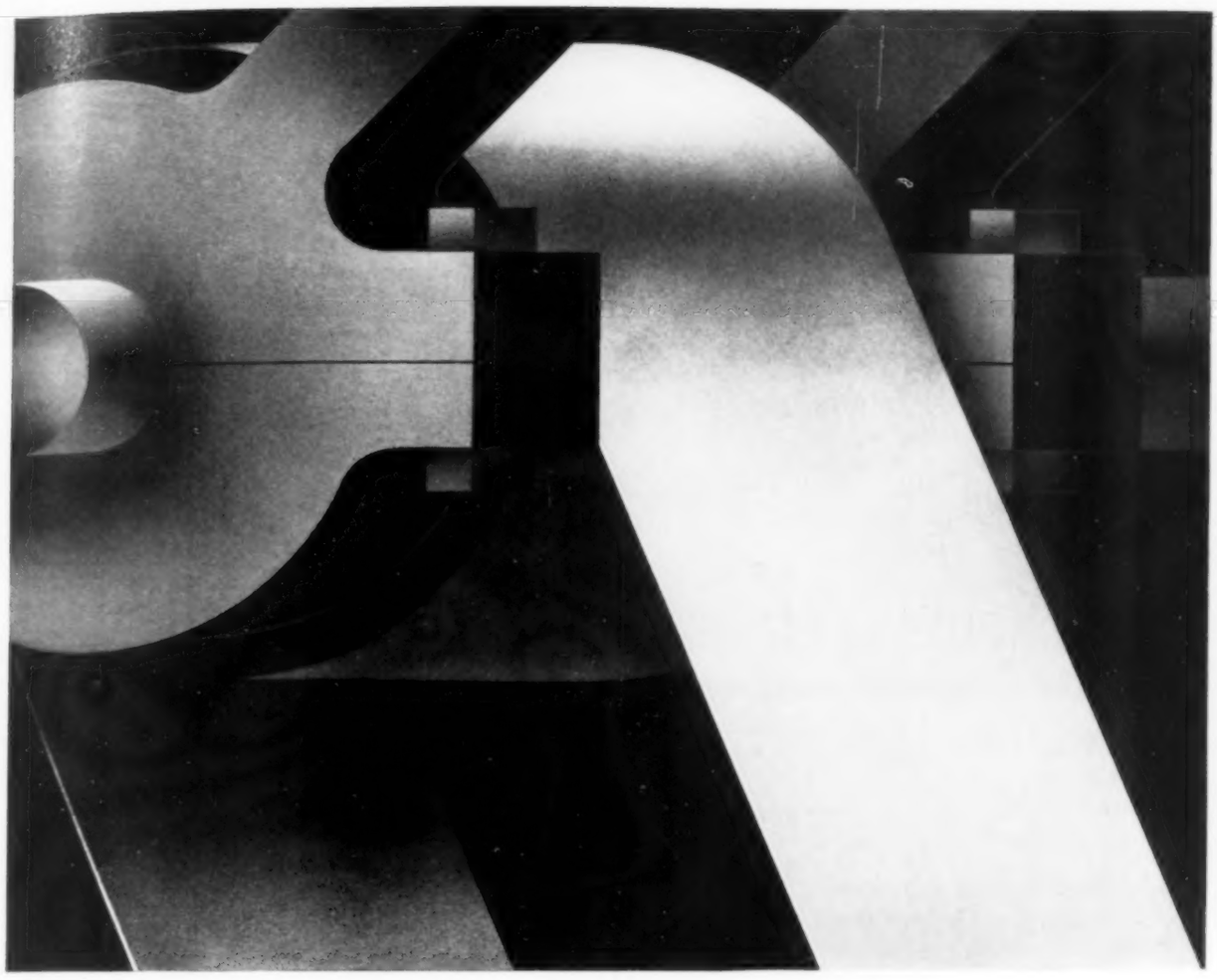
The greater hardness penetration obtained, when quenching hyper-eutectoid steel from a fully spheroidized prior structural condition, is probably due to the effective carbon, at the time of quenching, being close to the eutectoid composition (the excess carbon or carbides being in a difficultly soluble state or soluble only at a much higher temperature). Quenching the same type of material from a prior structure which is sorbitic or partially lamellar pearlitic will produce a shallower type of hardened case, because under these conditions the material will react according to its true carbon content.

On carbon tool steels of eutectoid composition, the foregoing will naturally be reversed — that is, deeper hardening will be obtained by quenching from a sorbitized or lamellar pearlitic structure than from a spheroidized structure.

During a detailed study of the basic causes for the relationship between prior structure and hardenability, we have checked the findings of previous investigators, and find that the comparative rating of the prior structural conditions regarding the respective time to change completely to austenite (transformation rate) is approximately in the following order: 1. Sorbitic; 2. Finely lamellar; 3. Finely spheroidized; 4. Coarsely lamellar; 5. Coarsely spheroidized; 6. Very coarsely spheroidized; 7. Very coarsely lamellar.

The question as to whether the varying time is actually the result of greater solubility of the excess carbide constituents when present in their various forms, or whether this is entirely a matter of increased solvent power of the matrix, is open for further work and discussion.

Concluding the foregoing discussion of present day quality control for tool steels in the maker's mill, we may point to the importance of the care, technical knowledge and experience which must be exercised. The economic use of modern machinery and equipment in all industries is but the result of the progress which has been made in the production of superior tool steels. It will be recognized that the great amount of testing which has to be carried out during the making of tool steel is, therefore, an essential means of giving the consumer a quality product which will insure uniform and consistent service.



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(Publications continued from page 44)

Phosphorus in Steel; Its Determination by a New Method Using an Ammoniacal Water Solution of Molybdate. Iron Age, v. 99, 1917, p. 824.

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Alloy Steel. Patent No. 1,420,708, June 27, 1922.

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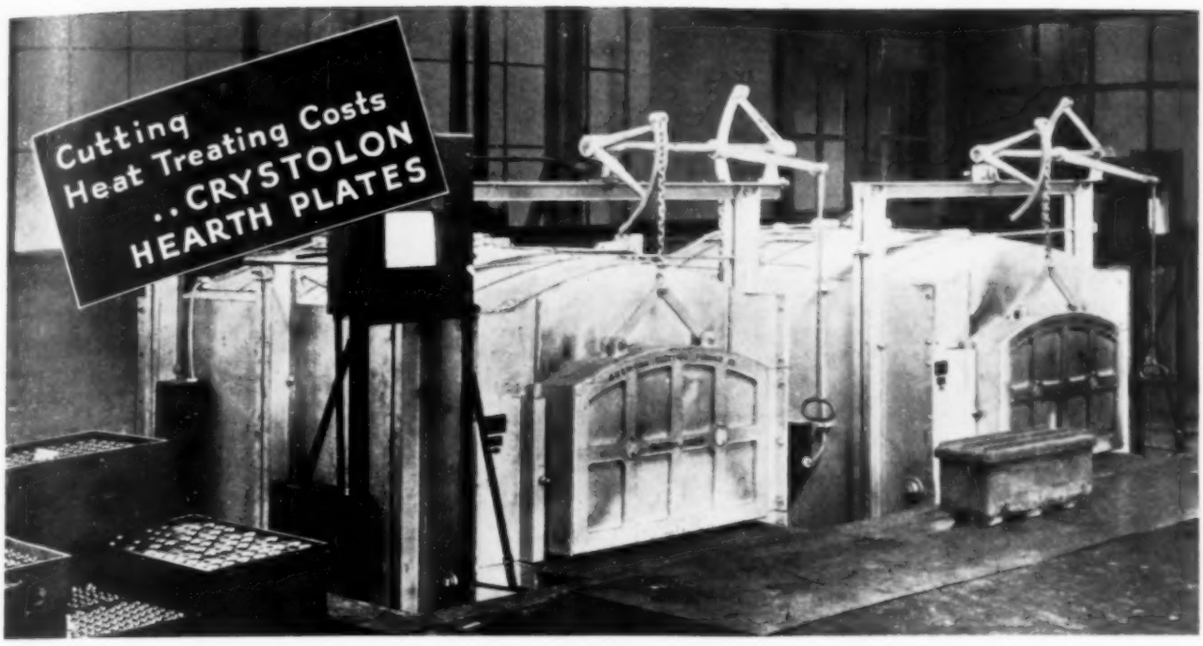

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BRIDGE WIRE

(Discussion begins on page 67)

accepted by mill inspectors. The surface smoothness of both varieties of wire is damaged by pickling and galvanizing (the heat treated wire much more extensively than the cold drawn), but the failure seems to be due to conditions inherent in all parts of the wire as made — that is, to an essential difference between the microstructure of quenched and tempered versus cold drawn steel.

With these conclusions Messrs. Swanger and Wohlgemuth agree.

As a result of an intensive study made early in 1929 (immediately after news of the failure) the present writer concluded that the then discoverable facts fitted into the hypothesis that the fractures were due to the inability of heat treated, galvanized wire to withstand a slowly creeping load. This hypothesis was discussed with numerous interested engineers and the investigators at the Bureau of Standards. All straight wires curving around the anchorage shoes and some unfavorably placed ones squeezed under the cable bands at the suspenders were bent so that the extreme fiber was stressed beyond the elastic limit; this stress was never relieved — in fact, added to it was a slowly increasing tensile load as the bridge was completed. Similar conditions exist (although of somewhat less intensity, as Swanger and Wohlgemuth demonstrate) in cold drawn bridge wire, but the essential difference, in my opinion, is that the heat treated wire is so stiff in its internal structure that it cannot yield readily at minor surface imperfections existing at such highly stressed elements and acting as "stress-raisers," and redistribute the stress to neighboring regions in the cross section. Hence a splitting type of fracture with no contraction of area occurs under slowly creeping loads beyond the elastic limit. Cold drawn wire, on the other hand, is much more plastic and has a low creep limit at atmospheric temperature, so the danger from scratches, notches or slag specks at the surface is much less.

If this hypothesis were true, it should be possible to duplicate the fractures occurring on the bridge by laboratory tests. H. F. Moore tried it at the University of Illinois on a few samples of spring wire — none of the suspicious bridge wire being procurable by him — with negative results (See **Metal Progress**, Sept. 1933). On the other hand W. A. Slater and M. O. Fuller at Lehigh University tested nine pieces of the heat treated bridge wire bent around a $9\frac{3}{4}$ in. radius and then loaded by increments starting at 84,000 psi. One broke while hanging overnight under the initial load, none withstood more than 201,500 psi., and all broke with a silky fracture, angular (no cup and cone), and no reduction of area.

Five testing machines were built at the Bureau of Standards for testing loops of wire, and 135 tests were made, with step-up loads starting at 90,000 psi. Only eight broke at less than the nominal ultimate tensile strength but none less than 120,000 psi. (after an increment of 30,000 psi.), while 34 had less than 20% reduction of area and therefore were classed by the investigators as a "brittle type of fracture." From their own tests Messrs. Swanger and Wohlgemuth concluded that "the results of the static [and step-up] loading under combined [flexural and tensile] stresses cannot be accepted as an explanation of the mechanism of failure of the wire on the bridge."

The present Editor would have proposed the word "complete" before "explanation" in the last sentence. As will be developed later, and even in the light of the tests at Lehigh and Washington, creeping loads cannot be entirely absolved from guilt. It is noteworthy that the difference between ultimate strength of heat treated wire and its yield point is 223,000—189,800 or 33,200 psi. The lowest breaks experienced at the Bureau of Standards occurred after stepping up the load 30,000 psi. Lastly the computed load on the cables at Mt. Hope when fractures were first found was 32,000 psi. This agreement of figures may be accidental, but then again may have some significance as to the minimum tensile strength of this heat treated wire when a tensile load is superposed on bending stresses beyond the elastic limit. Possibly a considerable degree of external restraint is an auxiliary requirement.

By further consideration of the special conditions existing where the bridge wire starts bending around the anchor shoe (the locus of most of the trouble), Swanger and Wohlgemuth were led to the supposition that the tension was not relatively quiescent but rapidly fluctuating. Extensive and valuable fatigue tests on both heat treated and cold drawn wire were then made and developed their endurance as galvanized, as stripped, and as machined down to solid metal. It was discovered that a hair pin of heat treated wire, bent around an anchor shoe and pulled taut, would break if the pull were fluctuated between 600 and 10,000 psi., whenever the experimental set-up was such that this range in tensile stress permitted the bent wire at the shoe to change its curvature by "spring back." In other words, minor changes in tensile stress induced major changes in flexural stress, beyond the endurance limit of the material, and fatigue failure resulted.

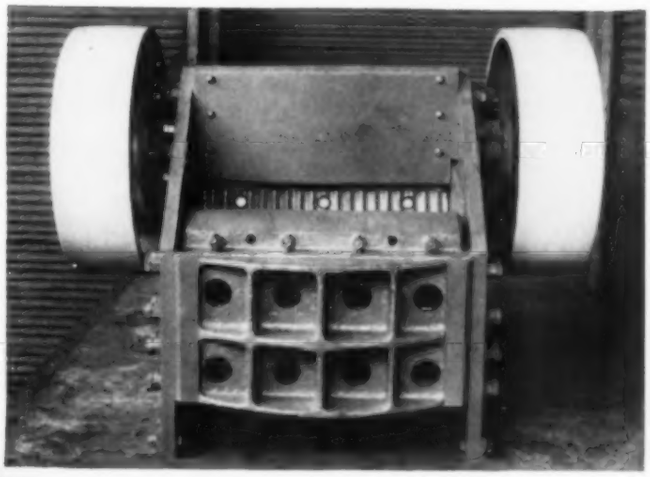
Since the investigators are able to break the heat treated wire in laboratory tests at low tensile loads, and the fractures certainly look like the ones that occurred on the bridge, the presumption is very strong that they have hit upon the right track. The only questions left to consider are

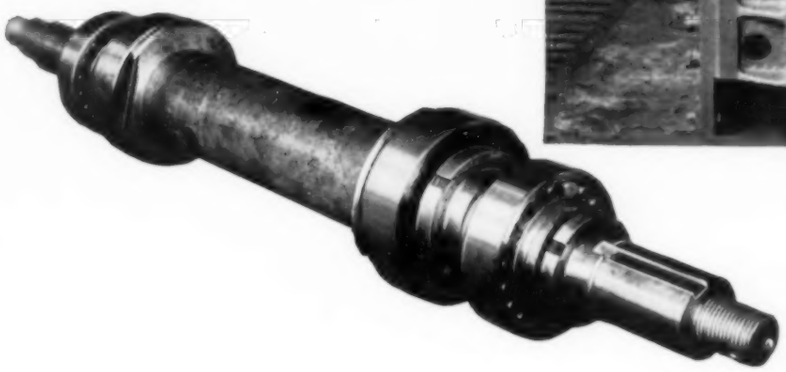
(a) Did rapid fluctuations of 10,000 psi. actually occur in the bridge wire?

(b) Why did so many wires break under the cable clamps at the suspender wires?

(Continued on page 84)

"There Can Be No Weak Spots IN A GOOD ROCK CRUSHER"





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BRIDGE WIRE

(Discussion begins on page 67)

(c) Why were the breaks at the anchorage concentrated largely in strand No. 1 of the east cable at the Bristol end of the bridge, and in strand No. 3 at the Portsmouth end of the west cable?

In answer to Question (a), it is unfortunate that Messrs. Swanger and Wohlgemuth could not extend their paper to include a mathematical analysis of the vibrations in the Mt. Hope bridge wire caused by side winds, the principal cause of rapid fluctuations, and an estimate of their effect on the tensile load. Lacking such analysis it is hard to imagine conditions that would cause a relief of 10,000 psi. in direct tension, when the stress in the wire due to its own weight is no more than 5,360 psi. at the anchorage. Wind vibration effects would probably be worst during early stages of spinning, when the individual wires are hanging free, for as soon as a strand is spun it is bundled together at intervals along its length, and of course the complete cable is tightly compacted and bound into a quite stiff unit. Yet no breaks occurred in the cable in this early, flexible stage; they were first observed when the bridge was nearing completion and the whole thing was relatively rigid.

A corollary of the fatigue hypothesis is that unbroken hairpins recovered from the bridge should already be in a badly damaged condition and should break after a very low number of additional stressings, as compared with hairpins made in the laboratory from straight wire. Perhaps the wide scatter of points in the S-N curve at top of the figure on page 66 may be so interpreted, although Mr. Swanger tells me that he has found no consistent differences in test results ascribable to prior use on the bridge.

Broken Wire on Straight Cable

As to Question (b), it is believed that the Bureau's investigators have paid too little attention to the breaks found along the cable, away from the anchorage. They say of the Mt. Hope bridge: "Approximately 20 were found under the saddle clamps at the cable bents. None were found at the main tower saddles. Eleven were found under cable bands in the side and main spans. Most of these breaks were at the outside of the cables and were believed to have occurred at points of localized stress where the saddle covers or bands had pinched the wire . . . and probably were not very significant."

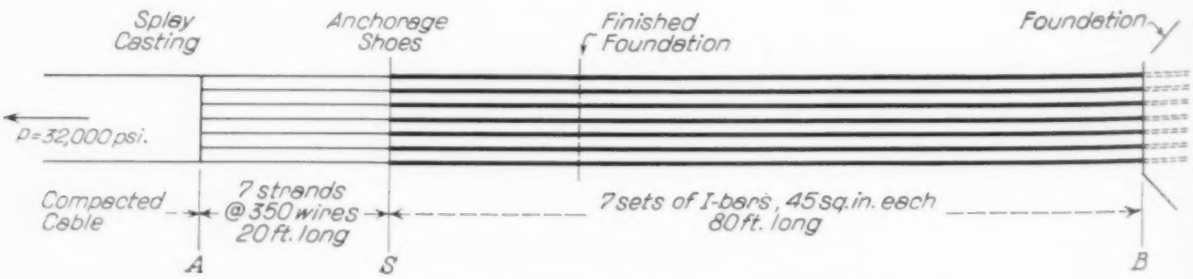
(One might well pause here to say — after the event — that **one** unexplained break is significant. I quote from **Metal Progress**, Sept. 1932: "During the development work on this wire, some 40-ft. lengths were hung over curved blocks on an idle crane girder and a platform on the lower ends loaded with billets, one or two added each day. Unexpected failures at the blocks and at low loads and deficient ductility resulted.")

Conditions were somewhat different at the Detroit-Windsor bridge made of the same wire. **Engineering News-Record**, Oct. 10, 1929, says: "Numerous breaks were subsequently discovered under the cable bands in the main strand at Detroit. . . . The principal difficulty in dismantling the main strand was occasioned by broken wires found at the suspender points; these wires became loose and entangled and others in one strand were so tightly squeezed to another strand that they had to be burned separately."

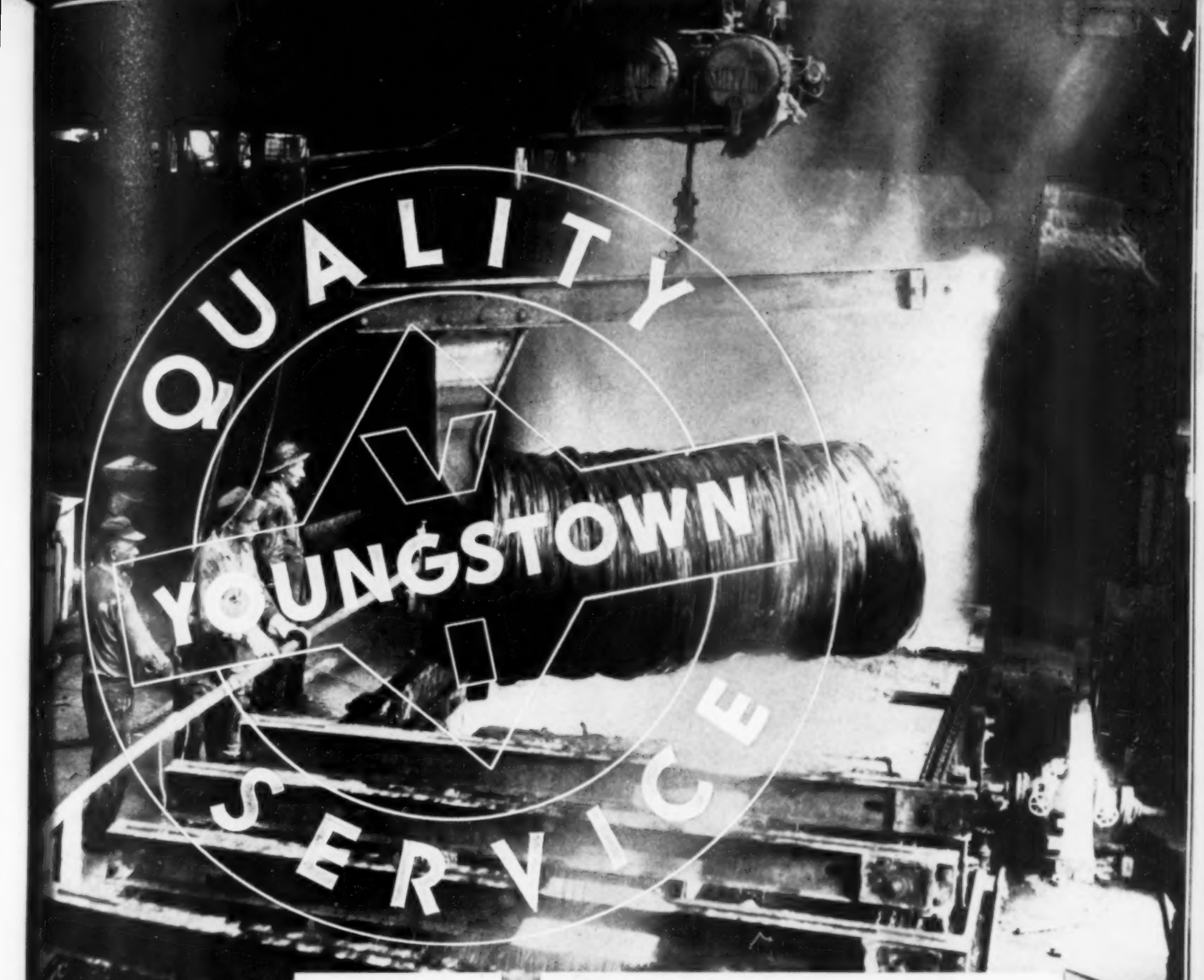
The creeping stress theory explained these breaks in rather sharply curved wires near the surface, where the cable is squeezed tighter by the bands, and the slowly rising stresses of subsequent bridge erection. If fluctuating tension in bent wires is responsible, the action cannot commence until the wires actually are bent (that is, until the clamps are tightened up), and consequently the damage started much later than at the anchorages and fatigue failure occurred in a comparatively short time in stiff, compacted cable — all of which seems rather unlikely.

The last question concerns the concentration of so many breaks in one strand of a cable. It is yet to be explained. The record of broken wires found on dismantling the Mt. Hope bridge is given in the table on page 61. The present writer is guilty of guessing that this was due to the presence of wire from two bad heats of steel. This is sufficiently refuted by the fact that 140 breaks were found in Strand 1 at the Bristol end, whereas the same wire at the Portsmouth end developed only four breaks. If any further evidence is needed, the erectors' records show that wire from not two but 21 heats found its way into these two strands! The guess was particularly unpardonable when a little elementary mechanics and algebra would have indicated sig-

(Continued on page 86)



Sketch of Seven Elastic Elements at Anchorage, Mt. Hope Bridge



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BRIDGE WIRE

(Discussion begins on page 67)

nificant changes in the unit load in the unbroken wires in a badly damaged strand.

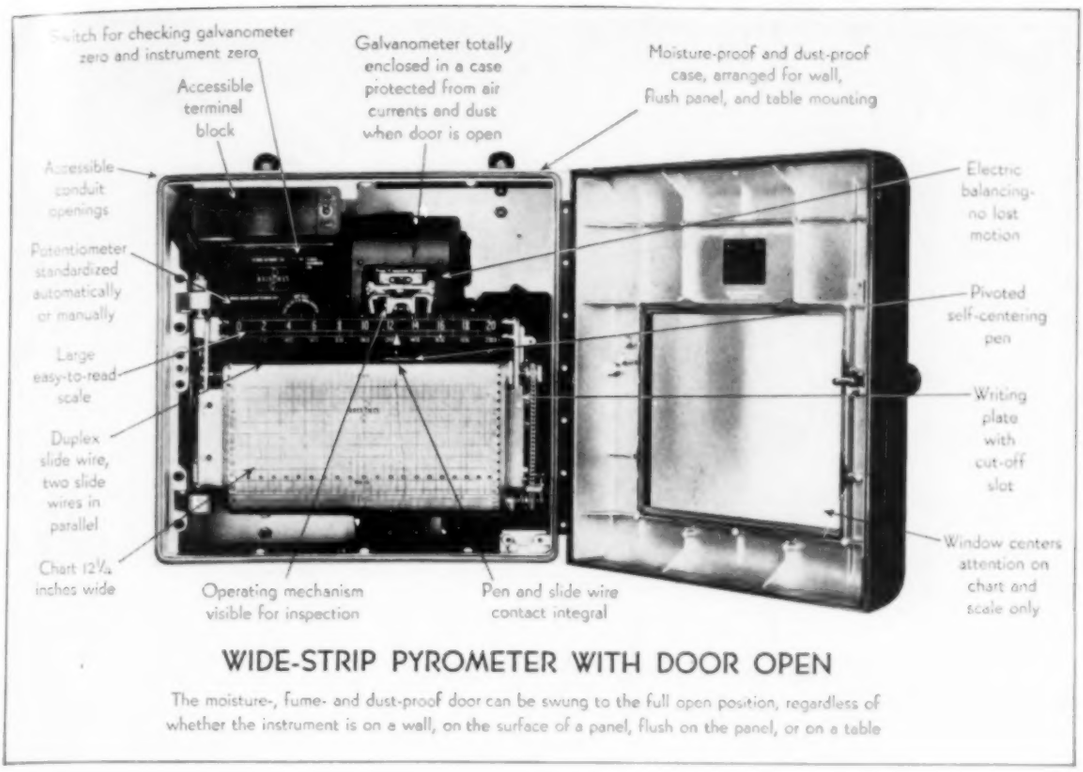
A well-compacted cable is a unit. For instance, it is almost impossible to pull out individual wires whose ends protruded without breaking the wire from a 10-ft. length of cable made up for test purposes. There is some evidence that the cable at Mt. Hope was not as closely compacted as it might have been, but nevertheless after compacting, the frictional resistance of wire to wire is so great that for preliminary computation one can treat a compacted cable as a unit.

Now suppose that such a compacted cable is made up of seven rods and that each rod is properly anchored to an unyielding foundation. The total load on the cable may equal P, and the load on each rod at each end of such a cable is $P \div 7$. Now if one of these rods breaks at one end, the total load is transferred to six remaining rods and the load per rod is $7P \div 6$ at the end having one broken rod, but it is still $P \div 7$ at the other end. That is to say, the unit load increases on the wires at an anchorage where there are broken ones, but the stress conditions at the undamaged end of the cable are not influenced by changes at the other end, short of entire collapse of the bridge. It follows, therefore, that a bundle of wires such as Strand No. 3 can be three-quarters broken at the Portsmouth end without requiring anything to happen at the Bristol end.

At the Detroit bridge the pit enclosing the eye bars and foundation girders had been filled with concrete up to the first pin. The elastic section then consisted of about 21 ft. of eye bar, concrete to shoe, and 30 ft. of wire, shoe to splay casting. At the Mt. Hope bridge each of the strands was anchored to two 12 x 1⅞ in. eye bars, 80 ft. long. They were to have been concreted in for 60 ft. of this length, but in describing the installation of hold-backs prior to dismantling the bridge, **Engineering News-Record**, Oct. 10, 1929, says, "Fortunately these eye bars had not been concreted in." The subsequent analysis will show whether this was "fortunate" or not; it also may give some clue as to why there was no undue concentrations of breaks in individual strands on the Detroit bridge.

General conditions therefore are as sketched at the bottom of page 84.

Prior to the time when any trouble occurred the loading on each of these seven units was approximately uniform, and the elastic extension of each unit the same. On the basis of a modulus of 29,400,000 all strands extended 0.261 in. in the 20 ft. between compacted position and shoe and the eye bars (45 sq. in. in cross section) extended 0.245 in. in the 80 ft. back to foundation. *(Continued on page 88)*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Duplex slide wire, two slide wires in parallel
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Operating mechanism visible for inspection
Pen and slide wire contact integral
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WIDE-STRIP PYROMETER WITH DOOR OPEN

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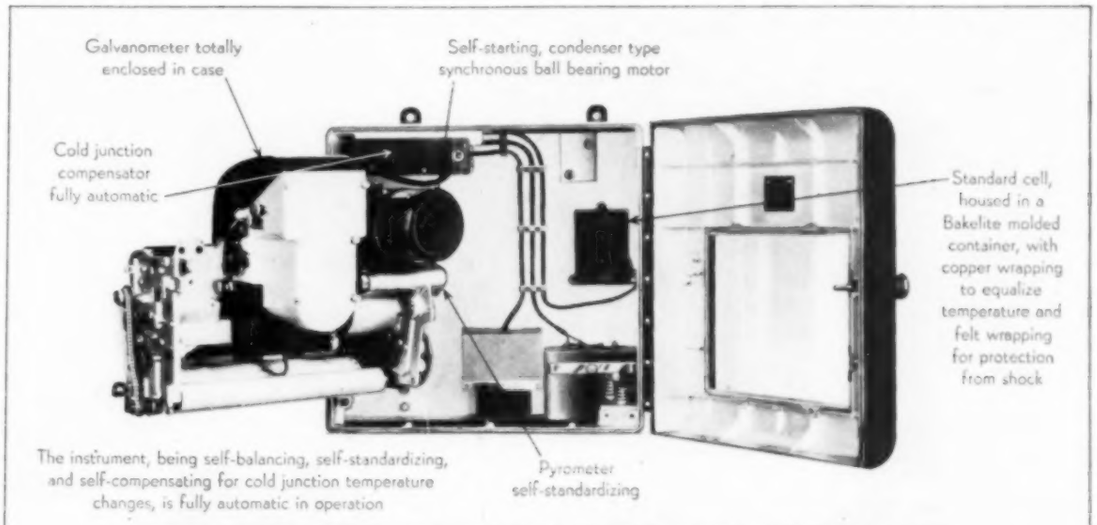
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BRIDGE WIRE

(Discussion begins on page 67)

Under these conditions the entire cable is carrying 2,368,000 lb. tension, each strand and mating eye bars 337,300 lb., each wire 962.9 lb., and each loop 1925 lb.

It is now required to find out what redistribution of stress will occur when a number of wires break in a single strand. Assume conditions in the east cable, Bristol anchorage, when 20 out of the 175 loops in strand No. 1 had broken, the whole cable being loaded at 32,000 psi. Instead of 2450 wires carrying the load there are now 2410, one broken loop putting two wires out of commission (both legs of the hairpin).

If the load on each wire in the six undamaged strands is M and the load on each wire in the damaged strand is N, then

$$2100\ M + 310\ N = 32{,}000 \text{ psi.} \times 74 \text{ sq. in.}$$

Also the load on each set of eye bars for each undamaged strand is 350 M and the set holding back the damaged strand is 310 M.

We can write an expression for the total elongation in the undamaged strand and its set of eye bars under the above loading, and this must equal the elongation in the damaged strand and its eye bars, since we have postulated no slippage in the compacted cable and no yielding in the foundation. This gives the second equation:

$$\frac{M \times 20 \times 12}{0.03 \times 29{,}400{,}000} + \frac{350M \times 80 \times 12}{45 \times 29{,}400{,}000} = \frac{N \times 20 \times 12}{0.03 \times 29{,}400{,}000} + \frac{310N \times 80 \times 12}{45 \times 29{,}400{,}000}$$

Solving this simultaneously with the first equation given we have:

M = 975.2 lb. equal to a stress of 32,400 psi.
N = 1032.2 lb. equal to a stress of 34,300 psi.

In other words, fracture of 20 loops has increased the load on the wires in the undamaged strands only 1.5%, but due to the elastic contraction of the large eye bars, the remaining wires in the damaged strand had their load jumped up 7.2%.

Conditions were much worse on Feb. 22, 1929, the first day when a careful search was made, and 65 broken wires were discovered in strand No. 1 of the east cable at the Bristol anchorage. Using the above method of computation, the wires in the practically intact strands were stressed to 33,100 psi., (an increase of 2.9% over a completely sound bridge) but the remaining sound wires in the failing strand carried 40,400 psi., an increase of 26%.

It is a matter of record that on the very next day "three-quarters of the wires were broken in that par-

(Continued on page 90)

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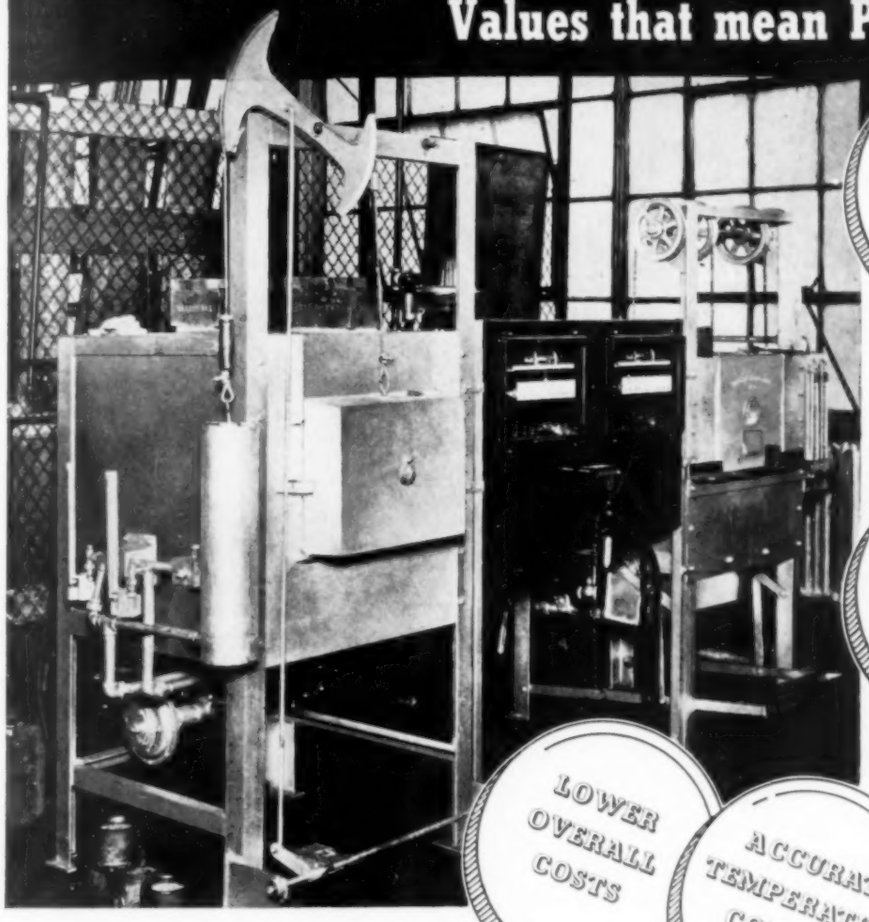
Values that mean Profits



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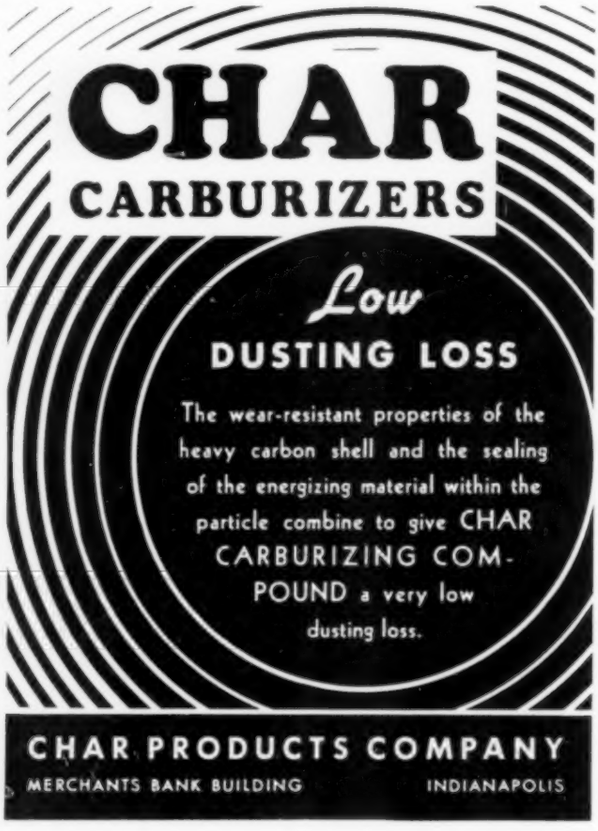
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BRIDGE WIRE

(Discussion begins on page 67)

ticular strand," and haste was made to lighten the stresses by hold-back clamps and taking all movables off the bridge. Taking the final conditions as found in the east cable of the Bristol anchorage (140 broken wires in Strand No. 1, the rest practically undamaged) the stresses were: In wires in undamaged strands 35,400 psi., an increase of 10.6%; in wires in Strand No. 1, 57,800 psi., an increase of 84%.

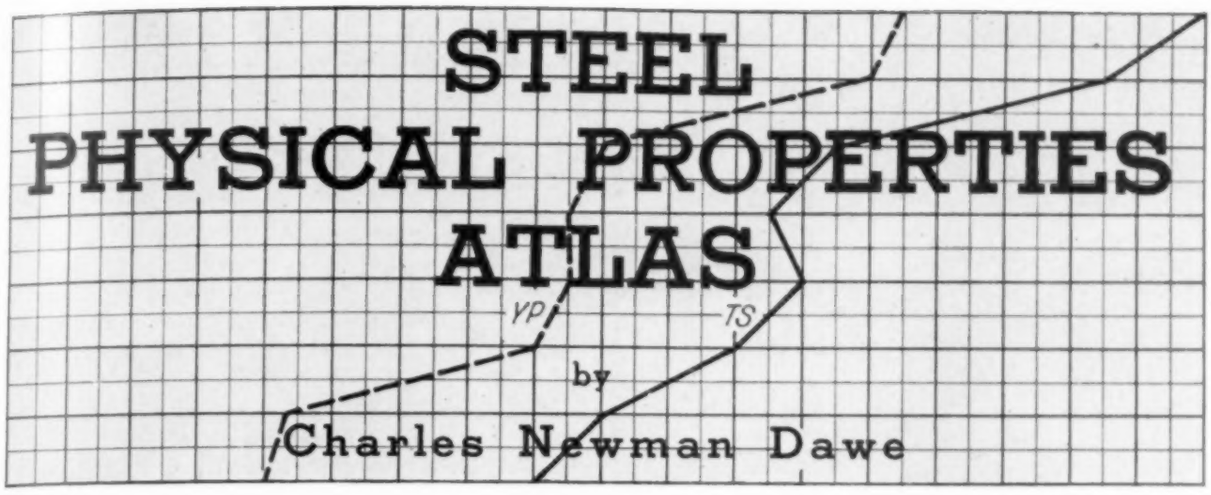
If, as above indicated, the concentration of breaks in definite strands was merely accidental, and would occur in the first strand which happened to develop a few breaks early in the history of failure, there might be some evidence of slippage in the broken ends back into the compacted cable, where the tendency toward elastic contraction on relief of load would overcome the friction, wire to wire. **Engineering News-Record** has such a record of movements of a paint streak just ahead of the splay castings. Maximum slippage in Strand 3 at Portsmouth anchorage was 3½ in., which progressed from 10 breaks on Feb. 27 to 129 on Mar. 9, and in the No. 1 strand at Bristol anchorage discussed above it was 1½ in. This article says "It is probable that by the time the line was painted considerable wire slippage had already occurred on the bad strand at the Bristol east anchorage. The data are merely indicative of the movements of 25 or 30 wires on the outside circumference." The record also shows a recovery of some of this slip when hairpins of new cold-drawn wire were spliced on the broken ends.

This rather brief review of some pertinent facts in this historic bridge failure indicates that, despite the enormous amount of careful and well-planned work done at the Bureau of Standards, a completely satisfactory explanation of the difficulty is not yet forthcoming. As before mentioned, the ability to develop fractures in the laboratory that look like the broken wire-ends from the bridge anchorages and at a combination of high bending and low tension loads indicates that we are close to the correct solution. It does not appear to be, however, the **complete** solution. In a number of instances, other factors also had major influence. What these factors are are still hypothetical. One may be heavy lateral constraint against movement at the surface. Another probably is a slowly creeping tensile stress.

Vulnerable though the bent heat treated wire has proven to be to fluctuating load with unchanged average intensity, it may be even more vulnerable when the average intensity is gradually rising. A series of "step-up fatigue tests" would determine this point.

Lastly, the surface condition of the heat treated wire was shocking. This refers not to the minor pits and scratches but to the deeper cracks which infested the wire and caused one out of every seven to

(Continued on page 92)



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BRIDGE WIRE

(Discussion begins on page 67)

ten tensile specimens to break with practically no reduction of area. Even though Messrs. Swanger and Wohlgemuth cannot find that these cracks affect the endurance of the wire more than the minor imperfections present everywhere, they were undoubtedly responsible for a large proportion of the rejects at the mill, and this would have been more ruinous if retests had not been allowed. (17% of this wire was rejected, as compared with 1.5% rejects of cold drawn wire shipped from the same mill to the Delaware River Bridge!)

Spring makers find similar cracks in the surface of heat treated springs after electroplating — possibly it is a characteristic action of the cleaning acid on the surface of any heat treated wire, no matter how well made. However the prevalence of such cracks as shown in the figure on page 62 is possibly sufficient to place one of these major surface defects within the region of stress concentration for practically all of the breaks that actually occurred on the bridge, and possibly was the immediate cause of the entire trouble.

Now what metallurgists and designers would like to know, even though bridge engineers will wisely stick to cold drawn wire, is whether heat treated wire with really good surface, either bare or rust proofed without surface damage, would be immune to the troubles that plagued the Mt. Hope bridge? In other words, were the failures due to the essential nature of the microstructure (relatively stiff and unyielding) or is this characteristic harmless unless the metal has gross surface imperfections?

Even though some questions remain unanswered, the researches so far have clear lessons that point to certain desirable changes in the design of large suspension bridges. The relatively small margin of safety of cold drawn wire (accepting all the implications of the endurance diagram on page 66) indicates that both bending and fluctuating stresses should be minimized as much as possible. This will involve three things:

(1) Anchor shoes should have as large a radius as possible.

(2) Stiff "keepers," carefully machined to correct line and curvature, should enclose all strands from within the splay casting to and around each anchor shoe.

(3) Eye bars should be concreted into the foundation as far up toward the anchor shoe as practicable.

Lastly, the practice of allowing a retest should be closely scrutinized. A plausible argument might be made for one when the original test fails to meet the specified values by a small margin once in a hundred times. But nothing can be said of a practice which permits the acceptance of material which shows deficient ductility in 10% of the tensile tests.